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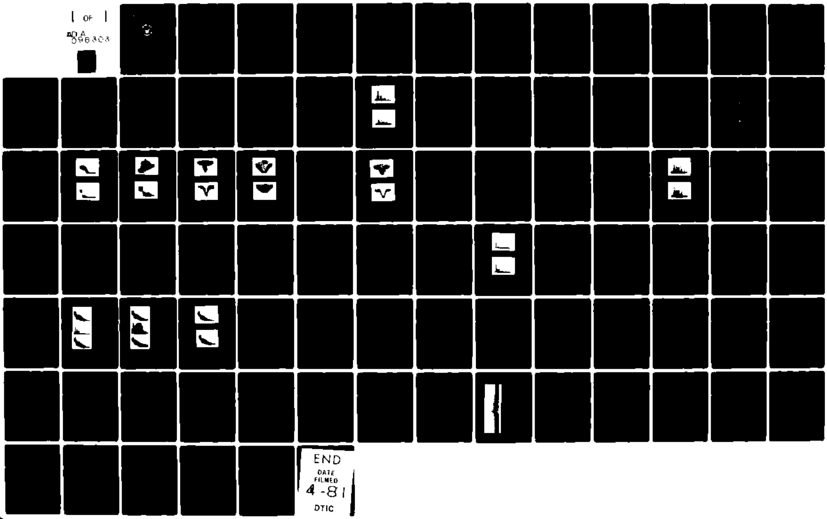

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INTERMODULATION PRODUCT SUSCEPTIBILITY
TESTING OF MULTICOUPLERS USING
WHITE NOISE

by

David William Smith

September 1980

Thesis Advisor: S. Jauregui

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# INTERMODULATION PRODUCT SUSCEPTIBILITY TESTING OF MULTICOUPLERS USING WHITE NOISE

by

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Lieutenant, United States Coast Guard
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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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September 1980

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## ABSTRACT

The problem of intermodulation product susceptibility and its specification in multicouplers is discussed. The two-tone input and white noise loading methods for testing and determining specifications are presented with spectrum displays. An improved method of testing and determining multicoupler intermodulation product susceptibility specifications is presented.

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<u>TABLE OF ABBREVIATIONS</u>

| | |
|---|---|
| BSP | Bell System Practices (III.A. pg. 21) |
| CIRR | International Radio Communications Conference of the ITU (III.A. pg. 21) |
| CCITT | International Conference on Telephone and Telegraph Communications of the ITU (III.A. pg. 21) |
| dB | Decibel, logarithmic unit of power ratio |
| dBm | Decibel referenced to one milliwatt of power |
| DOD | U.S. Department of Defense |
| HF | Military High Frequency radio spectrum, 2-32 MHz |
| HPF | High Pass Filter (fig. 5(c.)) |
| IM | Intermodulation (I.A. pg. 13) |
| IP | Intercept Point (II.C. pg. 16 and fig. 3) |
| ITU | International Telecommunications Union, Geneva |
| KHz | Kilohertz |
| LPF | Low Pass Filter (fig. 5(d.) and fig. 8) |
| MHz | Megahertz |
| MIL-STD | DOD established military standard (III.A. pg. 21) |
| NPR | Noise Power Ratio (III.C. pg. 22 and fig. 4) |
| RF | Radio Frequency |
| r.m.s. | Root Mean Square (II.D. pg. 23) |
| RS | Relative Suppression of IM below input signal level (II.B. pg. 16) |

UUT Unit Under Test, either the general purpose amplifier or the high dynamic range multicoupler.

# I. INTRODUCTION

## A. INTERMODULATION

Intermodulation products (IM) are spurious signals occuring at the output of a device, which are not in the input of the device or network. They are caused by nonlinear processing (e.g. overdriven amplification) of two or more input signals. The spurious signal is called "in-band" if it occurs within the bandwidth of interest and called "out-of-band" if it occurs outside the bandwidth of interest. In-band IM can cause degradation of system performance. In-band IM can occur on the frequency of a desired signal and with a larger magnitude masking the desired signal. In-band and out-of-band IM utilize part of the network's output power. This can decrease the device dynamic range, degrade desired signals and cause the network to go into saturation or other nonlinear operations. This in turn causes the generation of additional IM which yields further degradation.

Two or more strong input signals may be enough to start the generation of intermodulation products. IM generally occurs in any device when it is operated in or near the nonlinear region and has several input signals within its input bandwidth. The point of concern is how large are these IM products and how much can the system tolerate.

## B. THE MULTICOUPLER

In any area of communications, military, commercial, or amateur, one of the major building blocks of a system is an amplifier. This device may appear in many applications. It may also have many ports. One such device is called the multicoupler. It connects multiple receivers or transmitters to a single antenna or single operating position.

The particular device of interest here is the receiving multicoupler which couples a single input to several balanced outputs. The multicoupler operates at radio frequencies in the military high frequency (HF) band, 2 - 32 MHz. Single inputs may be from an antenna, preamplifier, or the output of another multicoupler. An amplifier stage is needed to overcome the losses and provide the overall 1 dB gain figure (plus or minus 1 dB): the object being to provide a single source to multiple users and not signal amplification.

This device is widely used in military electronics on fixed, mobile, shipboard and aeronautical platforms. Of particular interest is its use at U.S. Navy High Frequency Direction Finding (HFDF) sites. Here a single element or group of elements from an antenna array, such as a Wullenweber circularly disposed antenna array (CDAA), have to be fed to numerous users or processing points. Typically, these multicouplers have one input and eight outputs. They are often cascaded two or three deep (figure 1). This allows

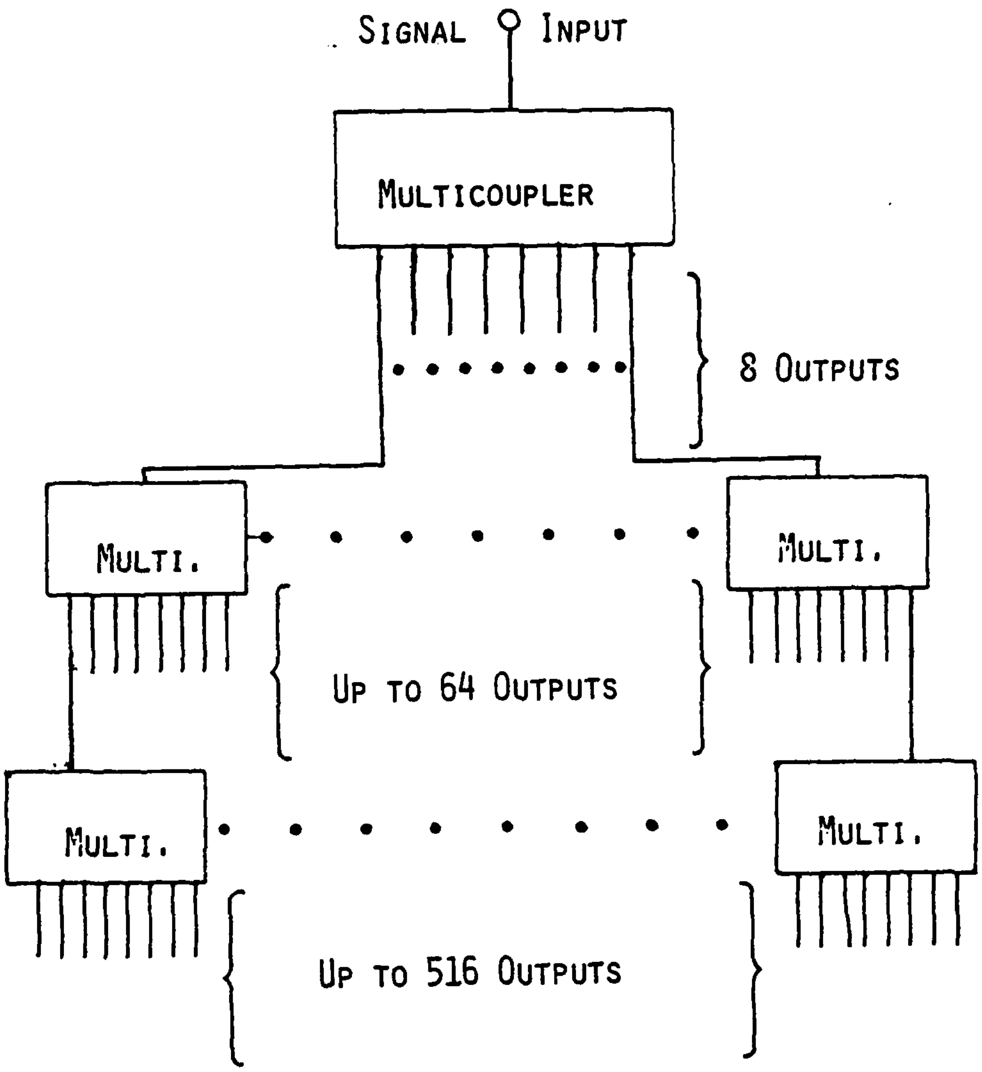


Figure 1. Multicoupler Chain

one input to be routed to as many as 64 to 512 processing points. Obviously, any errors or deficiencies occurring early in the chain will propagate to all subsequent processing points and degrade the entire chain.

Reference [1] discusses noise surveys made at various Navy HFDF sites. Results of these surveys show that two major sources of system noise were IM products and parasitic oscillations. Parasitics have a two fold effect. They not only put unwanted noise or oscillations into the system, but the resultant power usage of the oscillations reduces the multicouplers dynamic range and produces IM as a by-product.

The studies also showed that even in properly operating multicouplers (those which conformed to specifications) IM products and distortion were prevalent due to the high density of signals in the environment. With the next generation of multicouplers being readied for contract, there is a need to reexamine the current methods of specifying IM product susceptibility, the adequacy of such specifications, and the methods of testing for compliance with these specifications.

Current specifications usually call for the use of two tones or signals of a given voltage to be applied to the multicoupler input and the IM resulting should be a given number of decibels (dB) below the input signal level. A newer method of testing might be more realistic. For several years a technique of loading a circuit with white noise has

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been used for testing domestic and international telephone lines. The noise is applied to the circuit with a narrow frequency band which has been notched out or rejected. At the circuit output, the narrow stopband is reexamined and the increase in noise in the notch is used as the measure of IM, thermal noise and cross-talk caused by the circuit. This effectively simulates a single unused channel among many loaded channels and indicates the amount of interference the user of the clear channel would experience. Such methods can logically and realistically be extended to multicouplers, amplifiers and other wideband devices.

Section II addresses the two-tone method and section III addresses the noise loading method. Section IV contrasts sections II and III. Section V gives an evaluation of the white noise method. Section VI offers a method of specifying IM product susceptibility in multicouplers and a method for testing the device for compliance.

## II. TWO-TONE TEST METHOD

### A. SPECIFICATION

Typical specifications for IM susceptibility for Navy multicouplers are:

CU-1382/FRR 2 - 32 MHz

Better than 65 dB below two 0.5 Volt r.m.s. input signals

CU-1399/FRR 2 - 32 Mhz

Better than 60.5 dB below two 0.25 Volt r.m.s. input signals

The frequency or separation of the two signals are not specified although they are chosen so that the second and third order IM products fall inside the bandwidth of the device (e.g. 2 - 32 MHz).

### B. DETERMINING THE ORDER OF THE IM PRODUCTS

The order of the IM product is an indication of the combinations of the two test signal frequencies that result in the IM frequency. If two signals of frequencies f1 and f2 are used then the Order of the IM products are as follows:

2nd Order $f = f1 + f2$ or $f1 - f2$

3rd Order $f = 2(f1) + f2$ or $2(f1) - f2$

$= 2(f2) + f1$ or $2(f2) - f1$

4th Order $f = 3(f1) + f2$ or $3(f1) - f2$

$= 3(f2) + f1$ or $3(f2) - f1$

$= 2(f1) + 2(f2)$ or $2(f1) - 2(f2)$

and so on.

The total number of times the frequencies enter into the calculation indicates the order of the IM. Usually fourth order and higher are not considered significant due to their reduced amplitude and being far removed in frequency. IM products are usually identified by their order and relative suppression (RS), which is the number of dB (given as a positive number) that they are down from the two equal amplitude input signals. The IM products can be conveniently measured on a spectrum analyzer presentation of the multicoupler output, with a reasonable degree of accuracy. Figure 2 shows an example of a spectrum display with second and third order IM. Harmonics of the two input tones are also present at the input.

## C. INTERCEPT POINT

Another way of specifying IM susceptibility is with the third order intercept point (IP). This can be determined graphically. Output power of the fundamental versus input

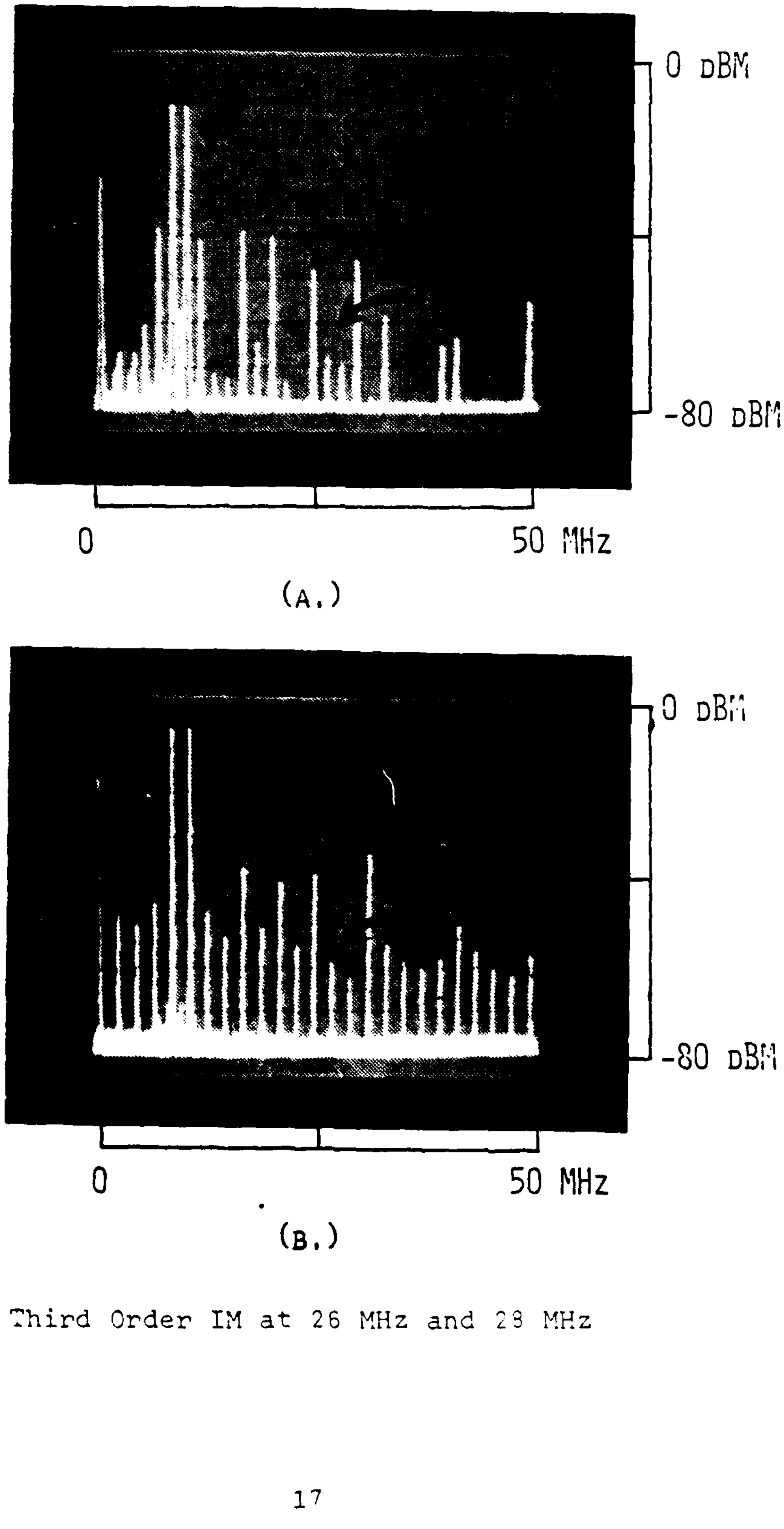



Figure 2. Third Order IM at 26 MHz and 28 MHz

power of the fundamental is plotted in dBm, then output power of the third order IM versus input power of the fundamental is also plotted in dBm. The straight line extension of the linear portions of each curve will yield a point of intersection. The value, in dBm, on the input power axis is the third order input IP. The value can be read off the output power axis and the point is called an output IP. The input IP value will be used here. The larger the value of the IP the more resistant the device will be to IM distortion. Figure 3 shows the IP for the high dynamic range multicoupler being evaluated. Reference [2] gives a more complete discussion of this topic. The intercept point is gaining in usage since it is mathematically independent of the input signal amplitude and can be specified for any order IM desired. This technique still relies on the use of the two-tone input.

## D. SHORT COMINGS

One short coming of the two-tone test is that it is not a good model of the real world HF spectrum. The multicoupler of interest is a wideband device, coupling the full 2 - 32 MHz range. The determination of the two-tone specification which gives the multicoupler sufficient IM resistance, becomes an empirical and inexact problem. Reference [1] presents survey results that show a receiving site on the East Coast of the United States suffering severe IM problems

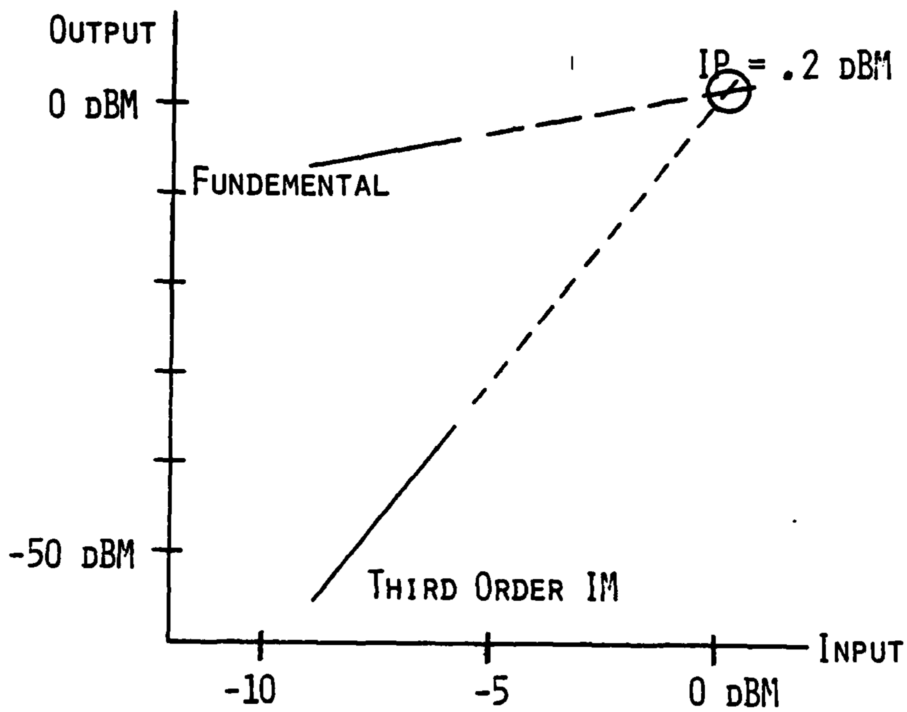



Figure 3. Third Order Intercept Point

from signals originating in Europe. The multicoupler at fault was the CU-1099/FRR whose specification has been given. The specification is inadequate for the signal environment encountered.

Secondly, the device has to be viewed as peak power limited for both the input power it can receive and the output power it can provide. Whatever the device's dynamic range, there will be a maximum limiting value of input power which produces the maximum available output power, bringing the device to the boundary of nonlinear operation. Any additional input will drive the device into the nonlinear region. Complex waveforms will randomly add in-phase due to the large number of frequencies and phases involved. If this in-phase addition exceeds the peak input power, the device will again be driven nonlinear. Hence, the phase characteristics of the input become important. The r.m.s. voltage or average power indications do not include this phase information. Therefore, the instantaneous voltage or peak power must be used to indicate the level of complex waveforms. If the period between input peaks, that drive the device nonlinear, is equal to or less than the relaxation time of the device, it will saturate and be held in saturation. The impact of this periodicity is not evident from a two-tone test source.

# III. WHITE NOISE TESTING

## A. BACKGROUND

White noise loading is widely used on telephone systems to measure the intermodulation and cross talk that occur in the system. Standards for the amount of noise that is allowed to exist have been established. These have ranged from the subjective opinion of the user to current Bell System Practices (BSP), International Telecommunications Union (CCIR and CCITT) recomendations, and U.S. military standards (MIL-STD-188). Reference [3] presents a detailed discussion of the applicatons of noise loading to telephone systems.

## B. NOISE LOADING TEST

The principle of the test involves loading a system, cable, repeater or component with white noise at the input. The white noise is generated by a noise generator such as a Marconi TF 2091B and is received with a noise receiver, Marconi TF 2092B. The white noise is generated over a bandwidth wider than the systems specified bandwidth and then bandlimited with the highpass (HPF) and lowpass (LPF) filters to equal the system bandwidth. The noise amplitude is uniform. The noise is applied to the unit under test (UUT). A bandpass filter on the noise receiver is selected

and switched in line. The receiver reference meter is then set to a reference level. Next, the generator stopband filter, which corresponds to the selected bandpass filter, is switched in line. The total output noise power is held constant by an output monitor (alc). The receiver reference meter is returned to the reference level by adjusting a set of attenuators on the receiver. The attenuator reading given is the noise power ratio (NPR) of the cross talk, intermodulation, and thermal noise that exists in the receiver passband.

## C. NOISE POWER RATIO

The NPR is read from the noise receiver attenuator, in decibels (dB) or picowatts. The NPR is the ratio of the full loading noise power, in a narrow passband, to the noise power in the passband after a matching stopband filter has been switched in. The rest of the system remains fully loaded, figure 4. The NPR can also be thought of as the number of dB an unused channel's noise is below the system loading level. The NPR includes the thermal noise power, also called baseband intrinsic noise [3], of the system. Sophisticated techniques are available to measure the portion of the NPR that is thermal noise, as well as that portion of the IM that is below the thermal noise level, ref. [3], [4] and [5]. For this dicussion, the total IM, cross talk, and thermal noise will be considered since all

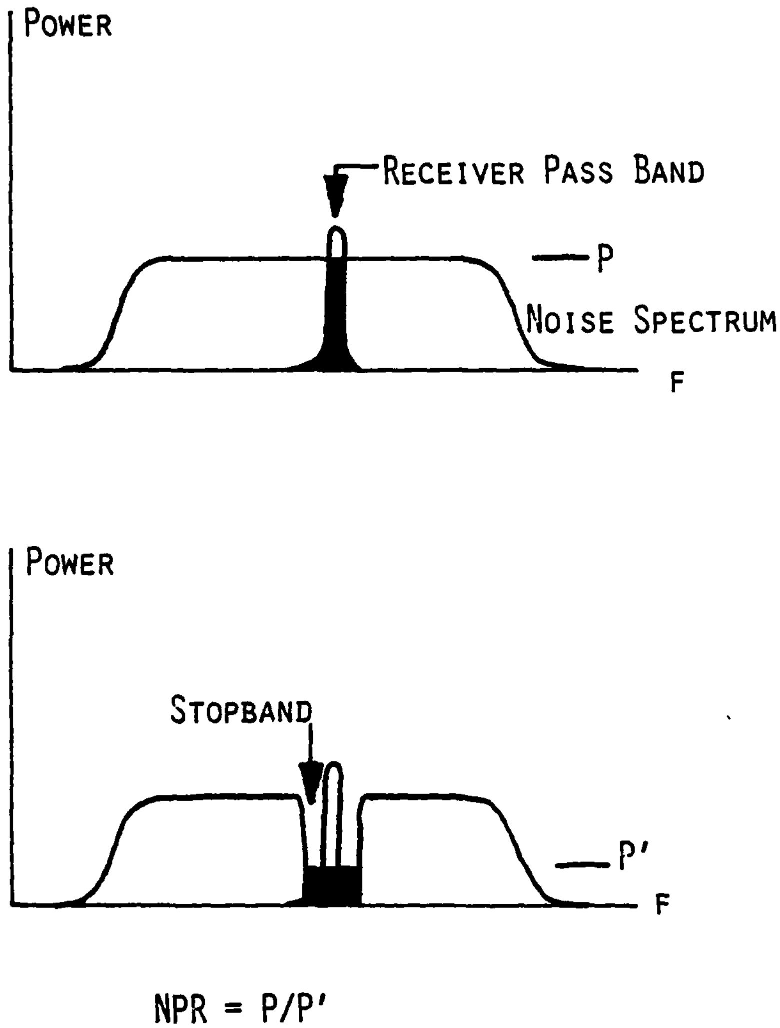



Figure 4. Noise Power Ratio

of these utilize the devices limited power and contribute to achieving nonlinear conditions.

D. APPLICABILITY OF NOISE LOADING TO MULTICOUPLERS

White noise testing has been of value in testing telephone translation equipment, microwave repeaters, and satellite transponders with up to 2700 channels or bandwidths up to 12 MHz. It is reasonable to extend this type of testing to multicouplers. The two-tone test measures IM produced by just two input signals. This is not a reasonable model of the HF spectrum. How many signals should be modeled in the passband? Appendix A shows the results of some samples taken of the 2 - 32 MHz spectrum. Any given 500 KHz segment, contained an average of 200 signals for the day and night measurements taken. Perhaps, a 200 tone test would be more realistic. If numerous 200 tone tests are made and averaged to develop some statistical descriptors, then what has been achieved is the white noise test, done piecewise.

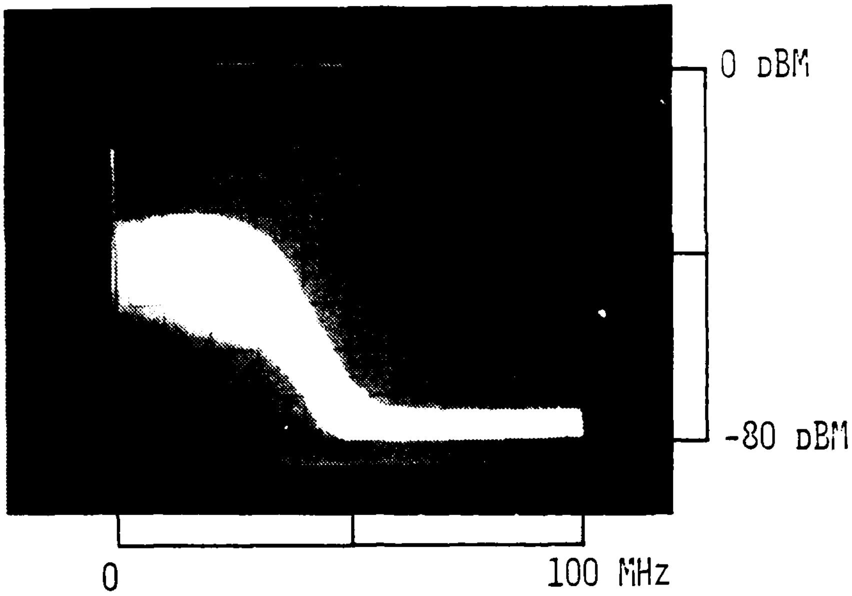
Examinations or processing of received HF signals is most often done over a finite bandwidth and not at a discrete frequency. The process will usually examine a small bandwidth (e.g. 3 KHz) of the 2 - 32 MHz available through the multicoupler. The concern is for low IM in the 3 KHz bandwidth of interest. The signal of interest must be available and not buried in IM generated by the other 29.997 MHz of signals at the multicoupler input. The white noise

test parallels this operation. It uses a wideband signal source and examines a small bandwidth for IN.

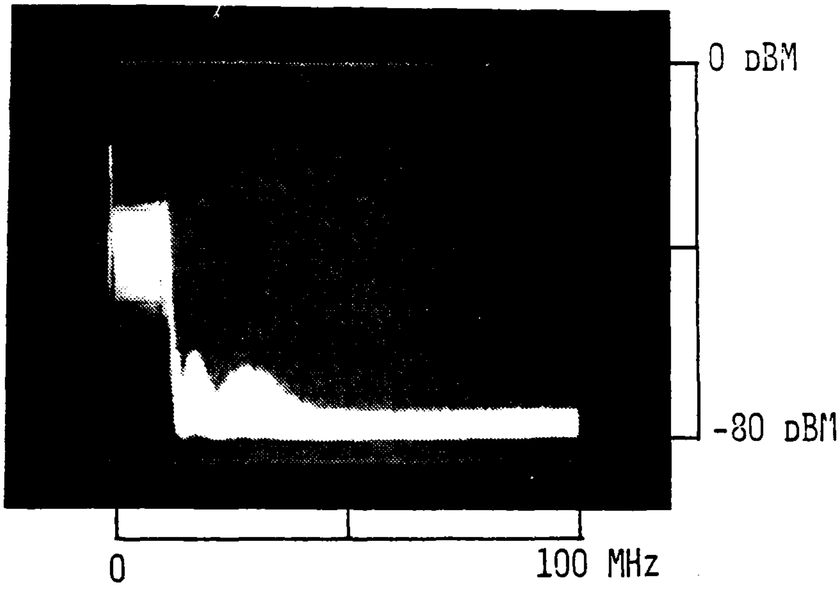
E. EXAMPLE SPECTRA

The following figures will show the use of the noise generator and receiver set. The set used was the Marconi OA 2090B, consisting of the TF 2091B Noise Generator, the TF 2092B Noise receiver, and the "B" version filters. The Marconi "B" version filters are those that comply with the current CCIR recommendation 399-1 (1974). The characteristics of these filters are given in ref. [3] and [5]. As an example, the stopband filter for 5.342 MHz has a 3KHz bandwidth at -70 dB, 8 KHz at -30 dB and 28 KHz at -3 dB. The corresponding bandpass filter has a 2 KHz bandwidth at 0 dB plus or minus 0.2 dB and at -25 dB the bandwidth must be less than 20 percent above or below the nominal cutoff frequencies [3]. Figure 5 shows the spectral characteristics of the noise generator output. Figures 5 (a.) and (b.) show the full and bandlimited outputs. Figures 5 (c.) and (d.) show the high pass (HPF) and low pass (LPF) filter output characteristics and figures 5 (e.) and (f.) show the 5.34 MHz and 11.7 MHz stopband characteristics.

Two examples of the effects of passing the stopband through a device are shown in figures 6 and 7. Figure 6(a.) shows the noise spectrum of the 11.7 MHz stopband at the input to a general purpose amplifier (HP 461A) and figure

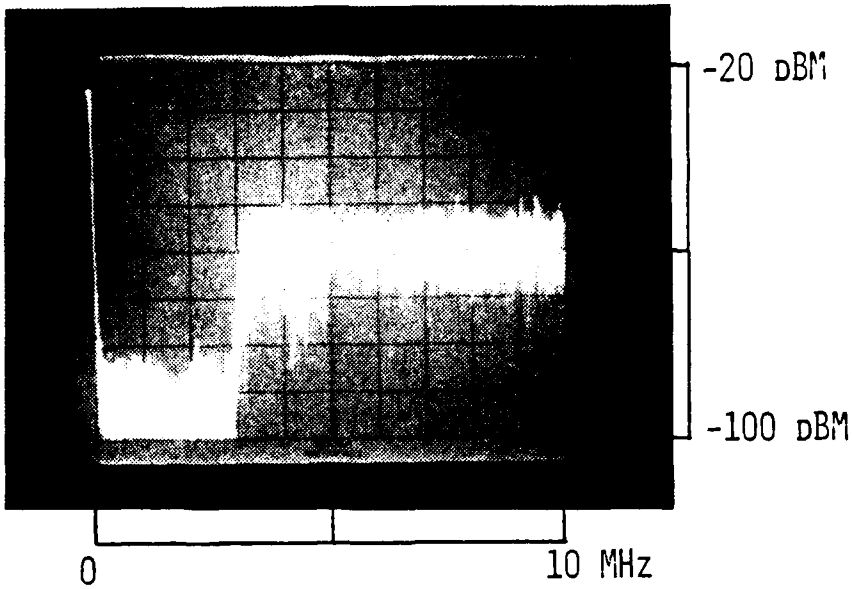



(A.)




(B.)

Figure 5. Noise Generator Output (A.) Full Spectrum
(B.) Bandlimited White Noise

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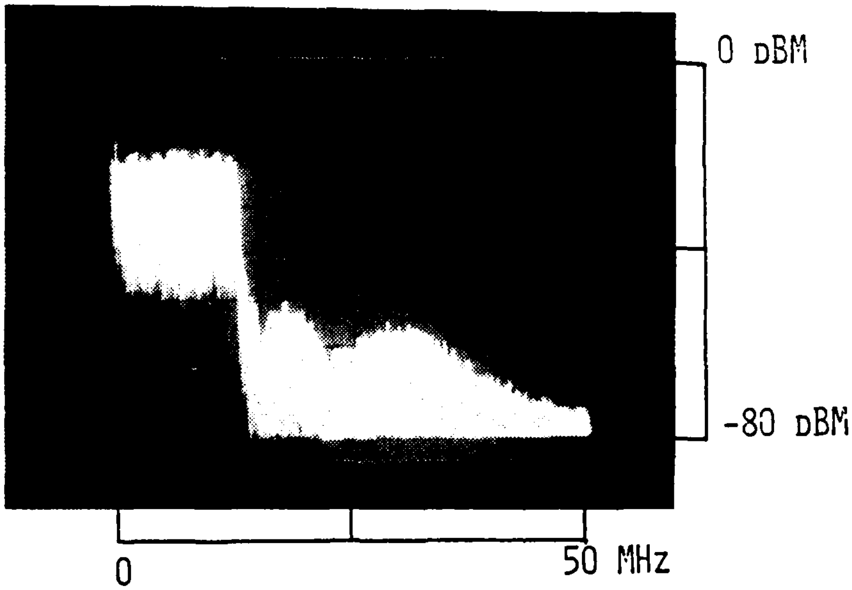
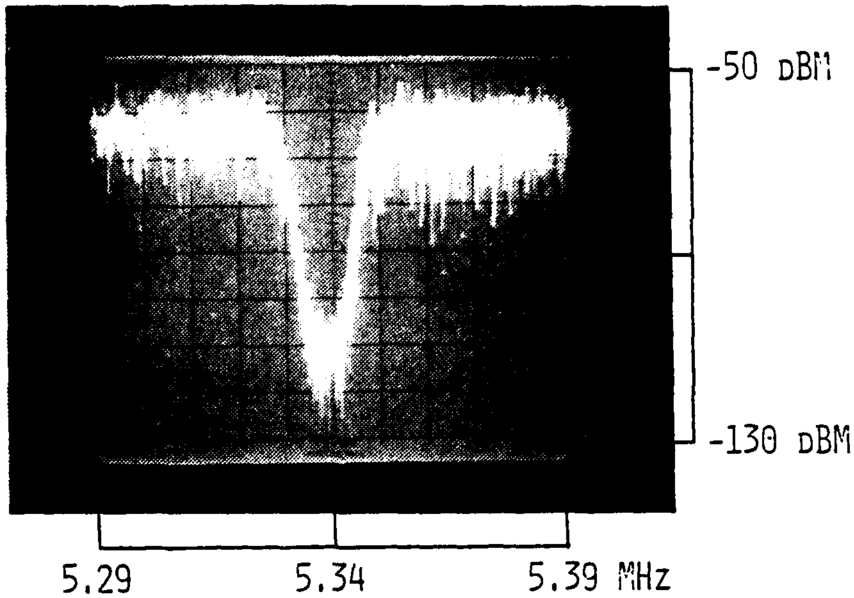
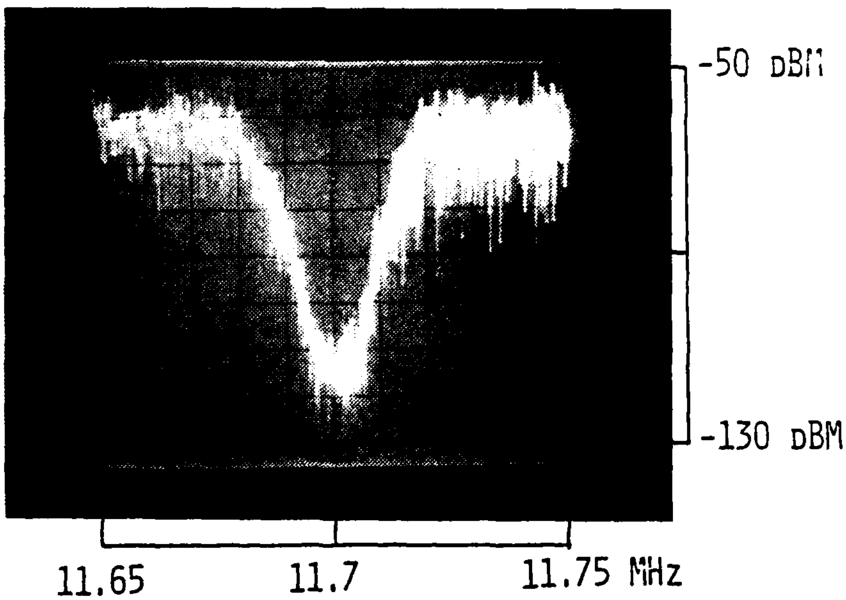



(D.)

Figure 5. Noise Generator Output (C.) 316 KHz HPF
(D.) 12,360 KHz LPF




(E.)




(F.)

Figure 5. Noise Generator Output (E.) 5.34 MHz Stopband
(F.) 11.7 MHz Stopband

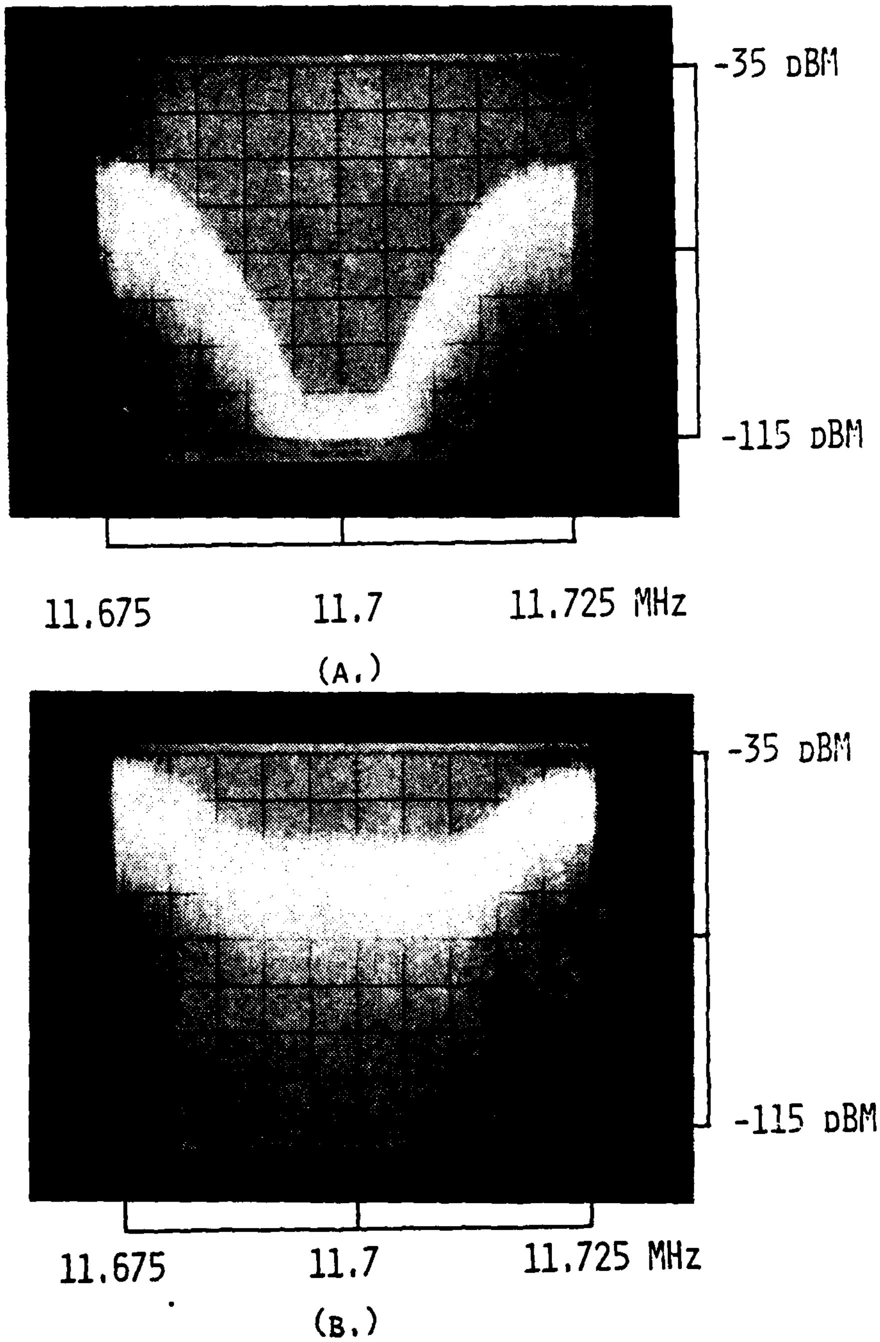
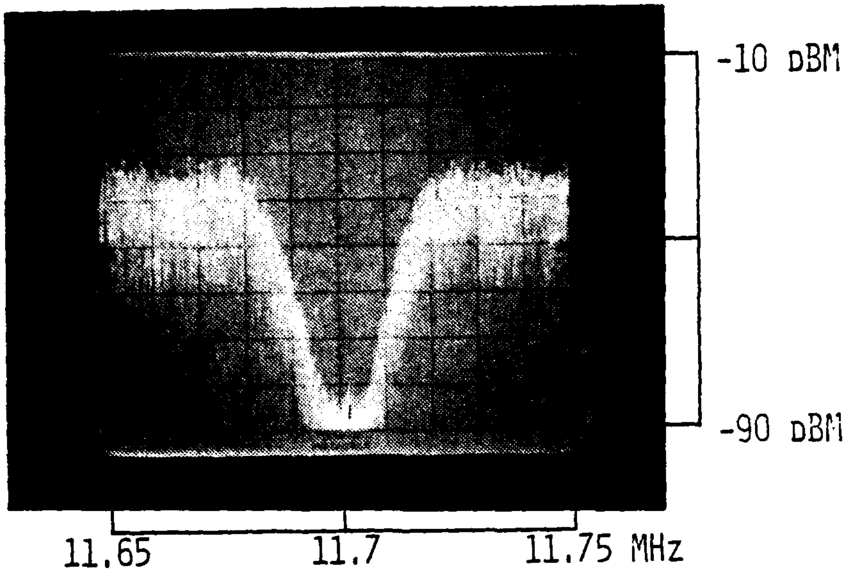



Figure 6. 11.7 MHz Stopband, Amplifier (A.) Input (B.) Output, NPR = 45.6 dB

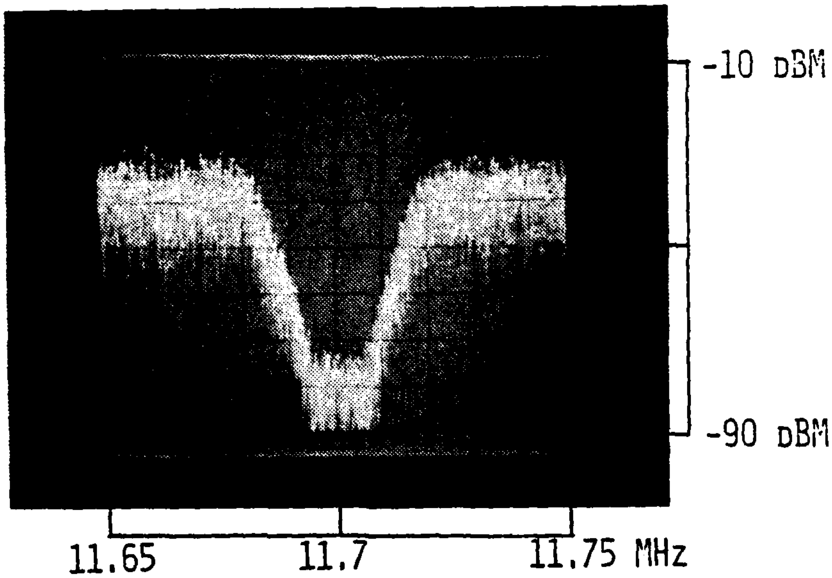
6(b.) shows the output response. The stopband has been "filled in" with intermodulation products. The NPR, measured by the calibrated noise receiver was 45.6 dB. The spectrum analyzer display indicates an NPR around 31 dB.

NPR = (-22 dBm Input) - (-53 dBm Noise in notch) = 31 dB

The spectrum analyzer horizontal sweep of 50 KHz with an IF bandwidth of 1 KHz resulted in the display averaging some of the noise at the edges of the stopband into the center, giving the appearance of a higher NPR. The fixed, center frequency 2 KHz bandpass filter in the noise receiver is not effected in that way and gives the more accurate value of NPR. Figure 7 shows a similar display for the input and output of a high dynamic range multicoupler that was undergoing test and evaluation. The NPR for the multicoupler was 48.2 dB.




(A.)




(B.)

Figure 7. 11.7 MHz Stopband, Multicoupler (A.) Input (B.) Output, NPR = 48.2 dB

# IV. TEST RESULTS

## A. ENVIRONMENT

Appendix A contains a summary of data gathered from a spectral analysis of the HF spectrum from 2 to 32 MHz. The data was examined to determine the distribution of signal amplitudes versus the number of observed signals. The combination of spectrum analyzer sweep time, display screen persistence and photographic film speed yield an average power or r.m.s. voltage sample. Any phase information is lost and determination of the peak amplitudes of the in phase component additions is not possible. Peak power or instantaneous voltages will exceed the levels shown. The data showed the mean signal amplitude was -100 dBm for the daytime survey and -95 dBm for the nighttime survey. Overall the mean was -98 dBm. The dynamic range of the signals was 85 dB (-30 to -115 dBm).

The total number of signals observed was 12295 of which 8214 were observed in the daytime and the remainder at night. No signals in excess of -30 dBm were observed. The noise floor of the spectrum analyzer was -120 dBm, hence signals below -115 dBm were not counted in order to exclude noise from the analyzer. The data was found to be adequately modeled by the log-normal distribution.

## B. IN-PHASE ADDITION

In-phase addition of the signals is an important consideration. The signal peaks will exceed the r.m.s. values and may drive the device into nonlinear operation. This requires that additional dynamic range be designed into the device. This is the crux of the intermodulation problem. Sufficient dynamic range and input power capability will prevent nonlinear operation and thereby prevent intermodulation. This dynamic range must account for the total input instantaneous voltage or peak power levels. How often the in-phase addition occurs and what are the maximum levels, are the points being argued. These two questions can be answered from a knowledge of the instantaneous signal voltage distribution (Appendix A).

Another parameter effected by the nature of the distribution is the required relaxation time. The relaxation time must be less than the average period of the in phase additions that exceed the dynamic range. otherwise the device may be held in a nonlinear mode, once driven into it.

## C. IM TEST RESULTS

An IM test using a single tone or frequency can be conducted. although this type of test is generally inadequate. No single tone tests were conducted. The two-tone and white noise loading tests were the two types of tests carried out.

1. Two-Tone Test

Tests using the two-tone method were conducted with two RF signals at 8 and 10 MHz, which were combined in a summing network and applied to the input of the unit under test (UUT), as shown in figure 8. The UUT output was observed on a spectrum analyzer and the display was photographed. The signal levels of both the input and output were measured from the display and with an RF r.m.s. voltmeter. Frequencies were verified with a digital frequency counter.

Figure 9 shows a typical input and output spectrum. Multiple tones were present at the input due to the harmonics of the fundamental frequency generated in the signal generator. These were partially reduced by filtering, but were not fully eliminated. Elimination resulted in insufficient input power to drive the test multicoupler nonlinear. Figure 10 is a graph of output power versus input power and third order IM power. The third order intercept point is also plotted. The multicoupler tested had a 1 dB compression point of +24 dBM. The test equipment used could not provide more than +18 dBM of input drive.

The power in an IM product depends on the power in the fundamental frequency and the frequency of the IM product itself. IM power is assumed to be a smooth and quasi-linear function as is the multicoupler output. Figure 11(a.) shows this in a graph of the second and third order

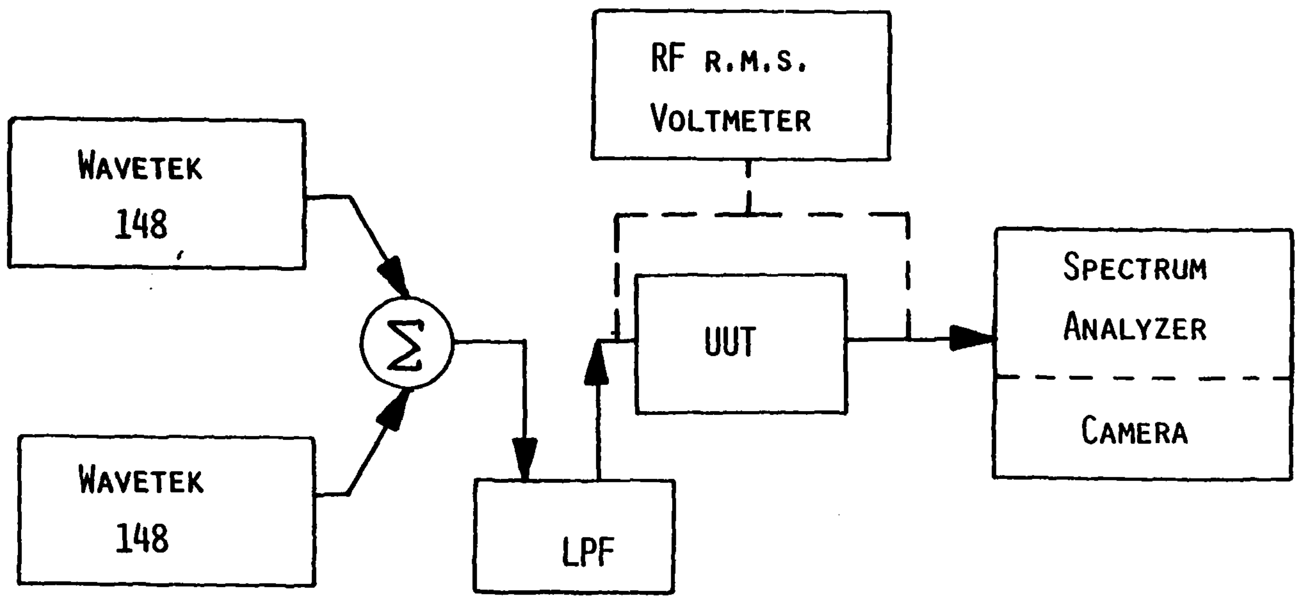
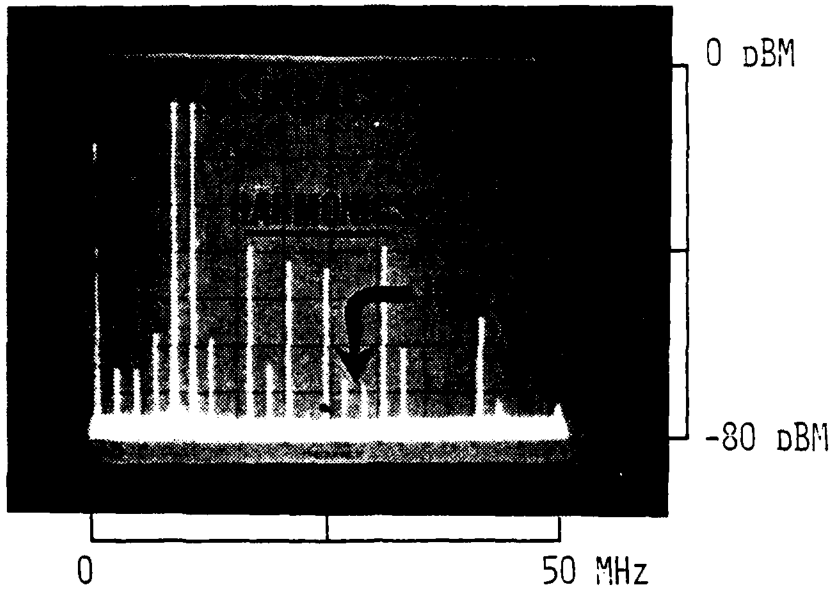
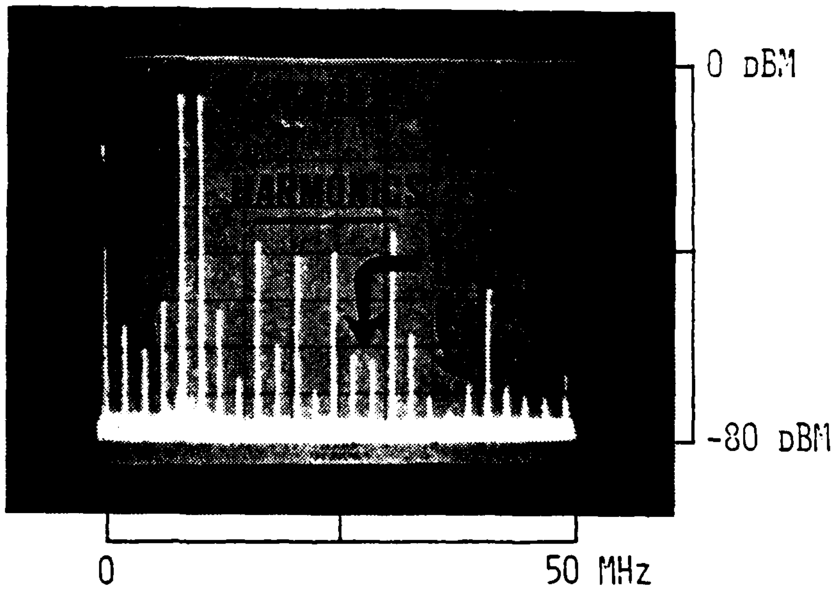



Figure 8. Two-Tone Test Equipment Configuration




(A.)




(B.)

Figure 9. Multiple Test Tones (a.) Input, (b.) Output.

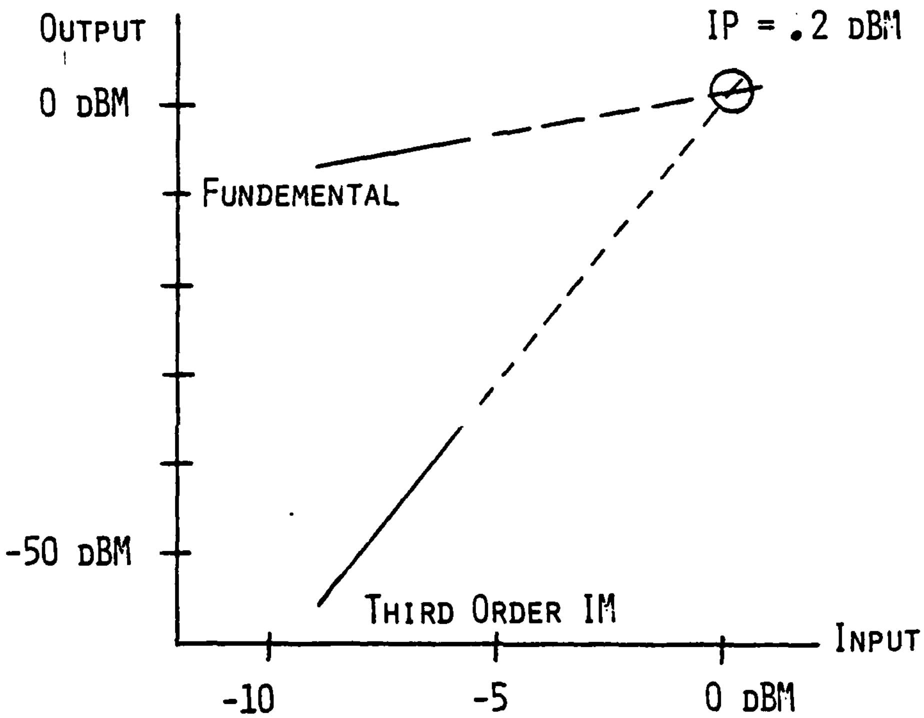



Figure 10. Input Power versus Output Power and Third Order Intercept Point

total IM power of the test multicoupler output. The test signals were 8 MHz and 10 MHz. Figure 11(b) shows the individual power in each of the four third order IM products. These curves show the variations that occur in the individual products. IM power should be measured by a total for the family of products and not by using one product as a representative sample.

2. White Noise Test

The output spectrum of the Marconi OA 2090B Noise Test Set is shown in figure 5. Technically the white noise driving the unit under test is bandlimited white noise. For brevity it will be referred to as white noise or simply noise, when no ambiguity will exist. The white noise produced by the TF 2091B noise generator is bandlimited by a 316 KHz highpass filter and a 12.360 MHz lowpass filter. These filters are used in testing 2700 channel telephone systems and give the widest bandwidth of white noise commercially available. Ideally the bandwidth of the noise should equal that of the system under test. The full system bandwidth must be loaded to simulate full load conditions, ref.[3, sec. 6.2], and it is that full load condition which causes the saturation and IM products, ref. [3, sec. 6.1]. In the tests conducted, full system bandwidth loading was not achieved. The white noise occupied only 35 percent of the system bandwidth of the multicoupler and 7 percent of the general purpose amplifier bandwidth. However, due to

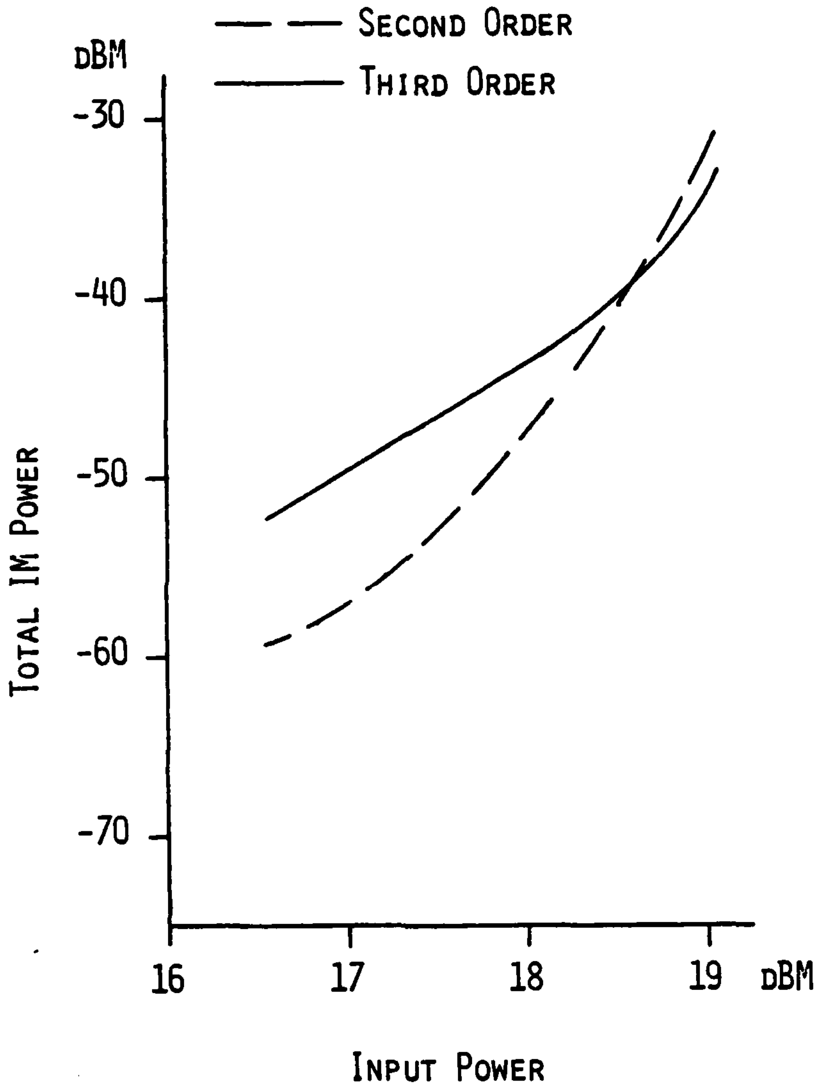



Figure 11(a.) Multicoupler Output, Second and Third Order Total IM Power versus Input Power.

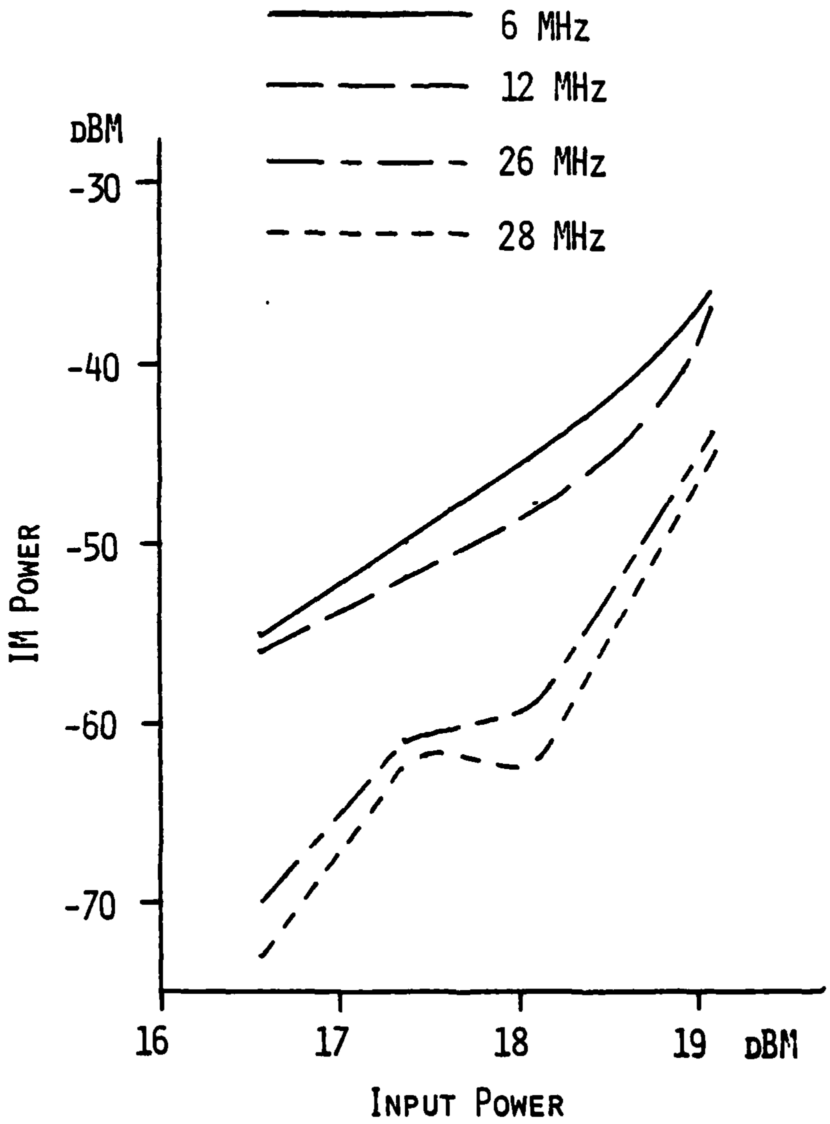



Figure 11(b.) Third Order IM Power versus Input Power

differences in dynamic range, the amplifier could be driven well into saturation, while the multicoupler remained in a linear mode. Hence, the actual IM products in both cases may be more severe than those shown.

Figure 12 shows the test equipment configuration for the noise loading test. The test was conducted as previously described in section III.B. The NPR for several levels of loading can be plotted to give an NPR curve similar to figure 13, for the general purpose amplifier, and figure 14, for the high dynamic range multicoupler. The NPR curve can be plotted in values relative to the maximum NPR loading level, figure 13, or in absolute values, figure 14. There are three regions on the NPR curve. They are the linear, maximum NPR and nonlinear regions. Reference [3] contains a detailed discussion of these.

The three regions are shown in figure 13. In the linear region, the signal to noise ratio remains constant. The thermal noise is significant compared to the intermodulation and a 1 dB increase in loading should result in a 1 dB increase in NPR. The signal to noise ratio can be expressed by:

$$SNRr = -10 \log [ a/(a-1) ]$$

SNRr is the SNR relative to the SNR at max. NPR

"a" = the predominant order of distortion.

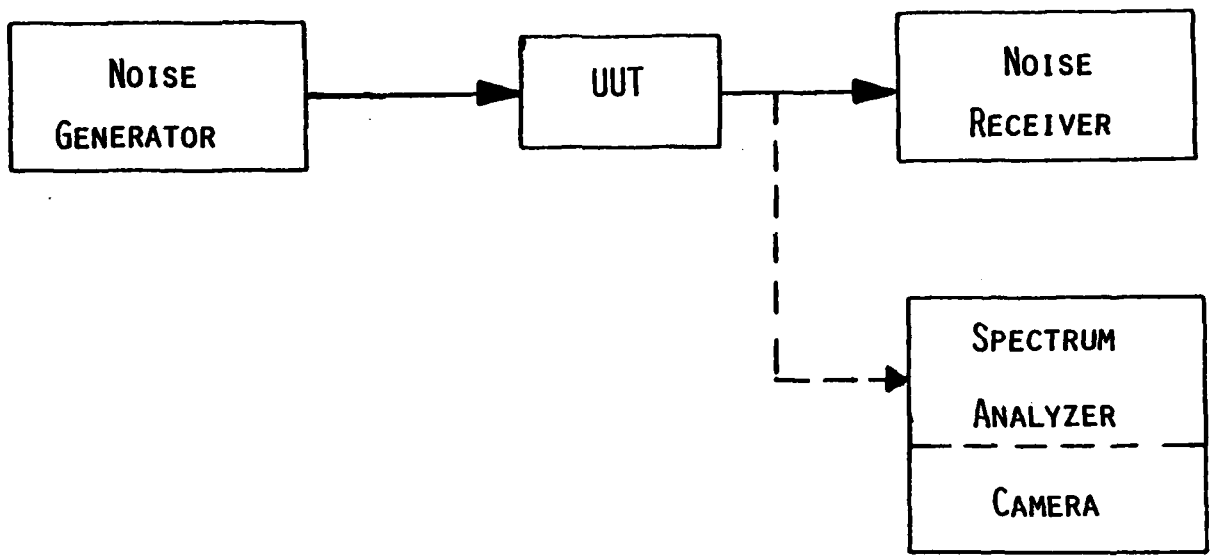



Figure 12. Noise Loading Test Equipment Configuration

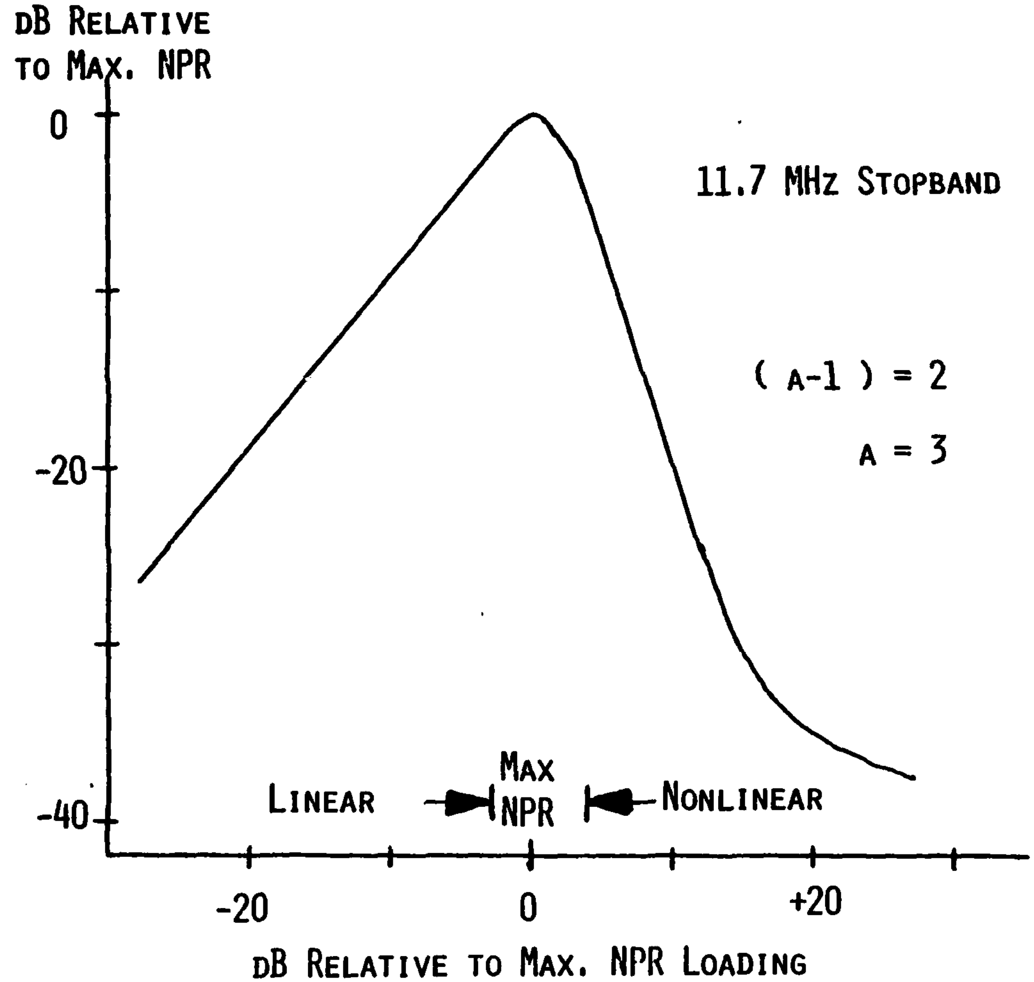



Figure 13. HP 461A Amplifier NPR Curve for 11.7 MHZ Stopband

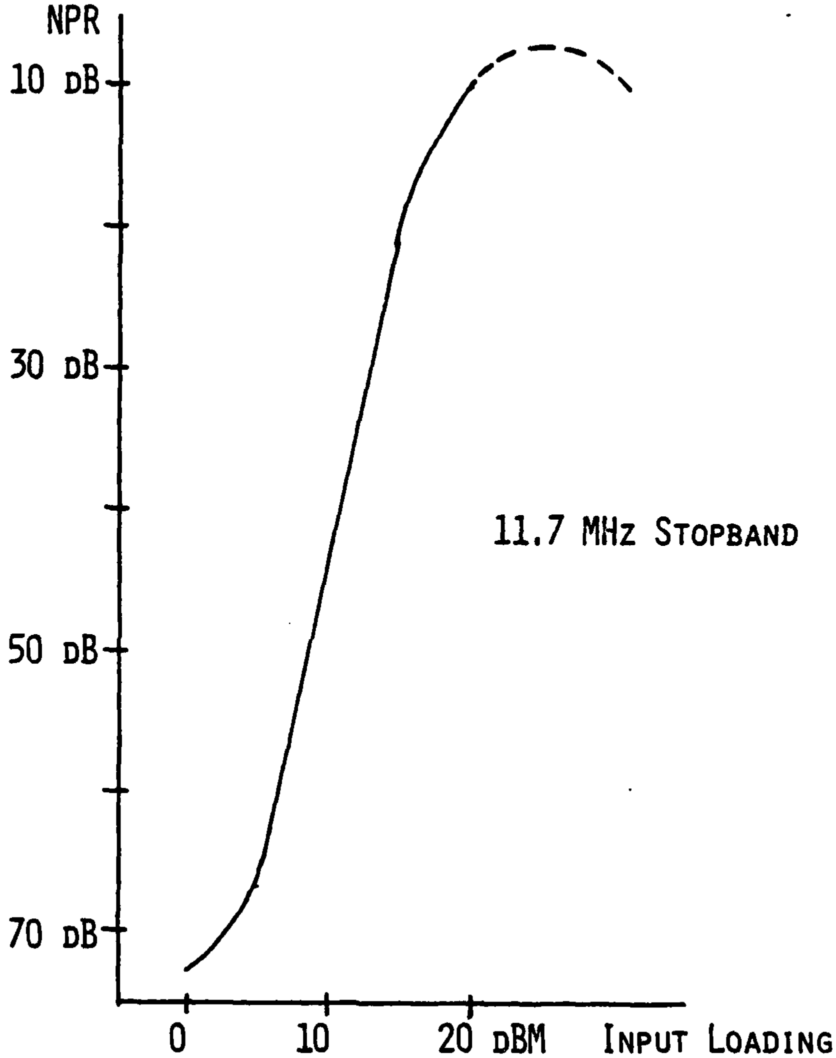



Figure 14. High Dynamic Range Multicoupler NPR Curve

In the nonlinear region, the thermal noise is negligible compared to the intermodulation. A 1 dB increase in loading decreases the SNRr by ( a ) dB and decreases the NPR by ( a-1 ) dB. The value of "a", the predominant order of distortion can be determined from the nonlinear region of the NPR curve. For example, in figure 13 "a" equals three since:

Nonlinear Slope = 2 = ( a-1 ) ; hence a = 3

In figure 14 the value of "a" can not be found since a nonlinear region could not be measured due to insufficient drive.

In the maximum NPR region, figure 13, the thermal noise is being overtaken by the intermodulation [3]. In the amplifier ( a = 3 ) measured in figure 13, the thermal noise is twice the IM at maximum NPR.

Thermal Noise Power = ( a-1 ) intermodulation power. [3]

In a second order system ( a = 2 ) the two would be equal at maximum NPR. In figure 14 the maximum NPR of the multicoupler was not reached.

In figure 13, the amplifier maximum NPR was reached at -23 dBm of input power. The amplifier had a specified maximum output of 0.5 volts r.m.s. into a 50 ohm load, that is +6.99 dBm. The 20 dB (plus or minus 1 dB) gain setting was used. Thus, the maximum input power needed to produce the maximum output was -13.01 dBm (plus or minus 1 dB). The

NPR curve shows the practical peak was reached 10 dB sooner at -23 dBm. It is this type of difference between the specification and actual operational capability that white noise testing should eliminate. The result will be more realistic specifications and device performance.

In figure 14, a 1 dB increase in noise loading produced a 4.5 dB increase in NPR instead of the expected 1 dB increase. It appears that the reason for this is that the thermal noise was not significantly larger than the intermodulation, as is usually the case. The thermal noise of this quality device was below the noise floor of the spectrum analyzer ( -120 dBm ) and could not be measured. A source of the IM products, which would exceed this low thermal noise level, appeared to be higher order IM products. Figure 15(a.) shows a low level input to the multicoupler. Figure 15 (b. ) shows fourth, eighth and ninth order IM products just appearing at -80 dBm. This level of IM would readily exceed the thermal noise level.

3. Comparison of Both Methods

It is difficult to carry out a strict comparison of the two-tone and white noise methods due to the different characteristics of the signal types involved. A preliminary comparison was made to identify areas of superiority of one method over the other. The comparison was conducted by separately applying either the two tones or the white noise of equal total r.m.s. voltage to the high dynamic range

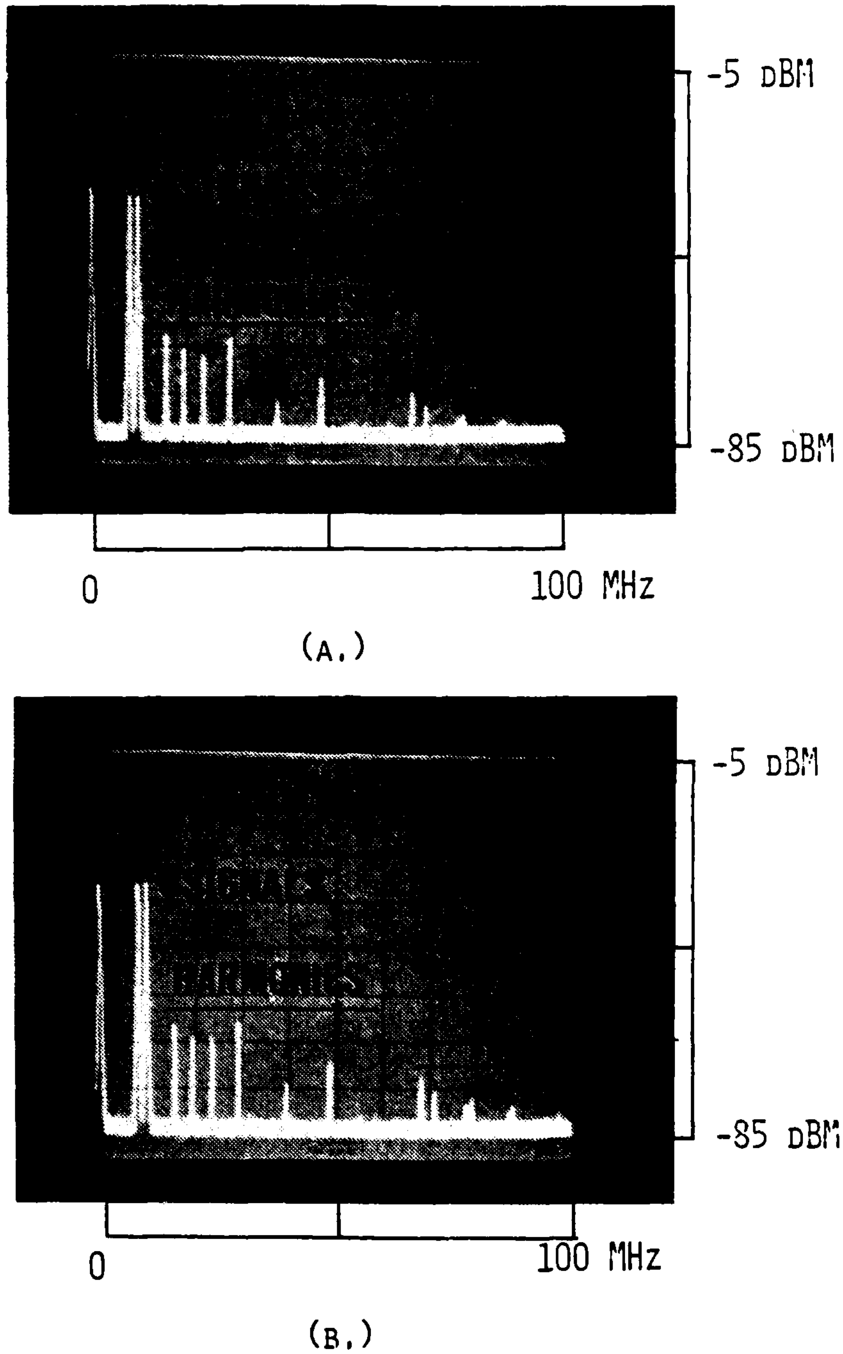



Figure 15. Tone Inputs (A.) and Low IM Output (B.)

multicoupler. The NPR and the relative suppression RS of the third order IM products were compared.

Figure 16(a.) shows a graph of the NPR for the 5.34 MHz and 11.7 MHz and the IM RS plotted against the input power. Figure 16(b.) shows the same NPR and IM RS plotted against the input voltage. There is no radical difference in these curves as would be expected with the multicoupler operating well within the linear region of the dynamic range. Figure 17 shows the relationship of the IM RS to the NPR graphically. This relationship is near linear with the correlation of these curves to a straight line being 0.91 for the 5.34 MHz curve and 0.99 for the 11.7 MHz curve. Therefore, for linear operation either method of testing might be sufficient, but this is not the case for nonlinear operation.

The level of IM in a device varies with the frequency. For the multicoupler the NPR had different values in each of the two stopbands. These were closely related as shown in figures 16 and 17. The NPR at 5.34 MHz and 11.7 MHz differed by 0.4 to 2.2 dB. This means multiple samples must be taken. With several sets of stopband/bandpass filters, several frequencies within the passband of the device can be measured to check for radical variations in the NPR. Unless several two-tone tests were made at a variety of frequencies, a significant abberation could easily be missed. Such an increase of IM in one section of the

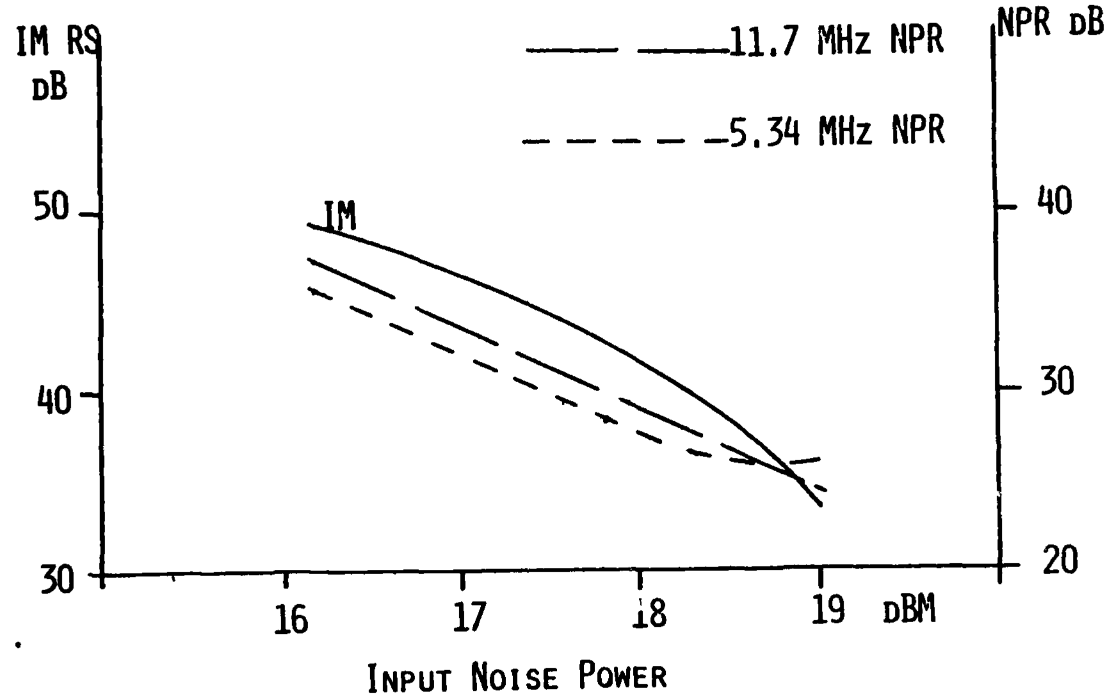



Figure 16a. IM Relative Suppression and NPR versus Input Noise Power

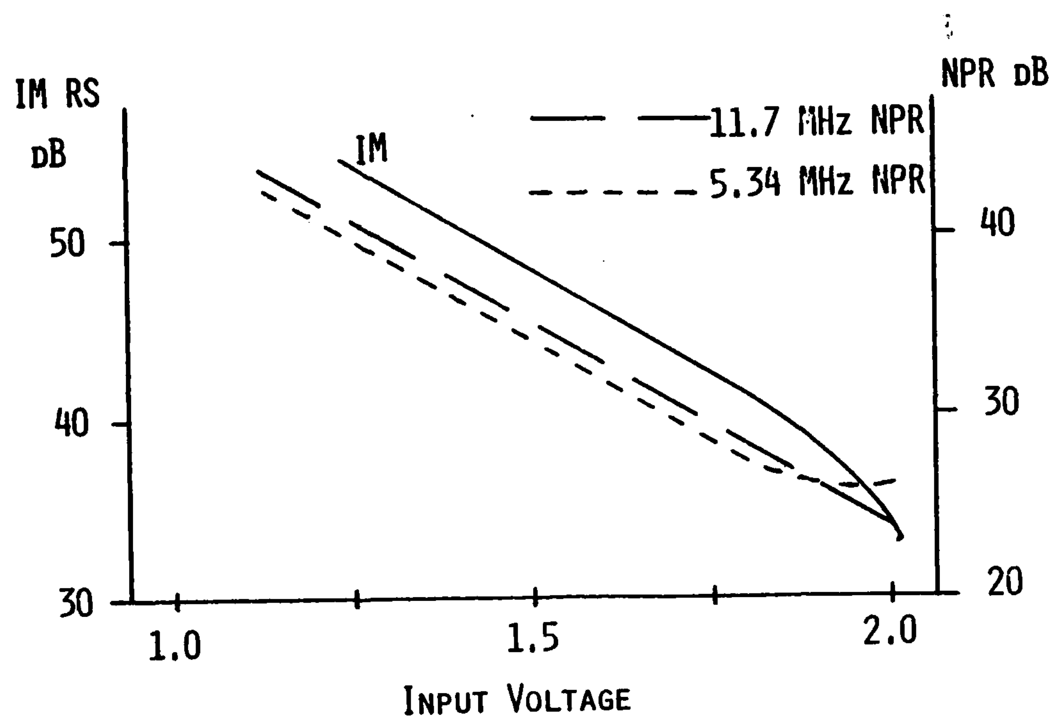



Figure 16b. IM Relative Suppression and NPR versus Input Voltage

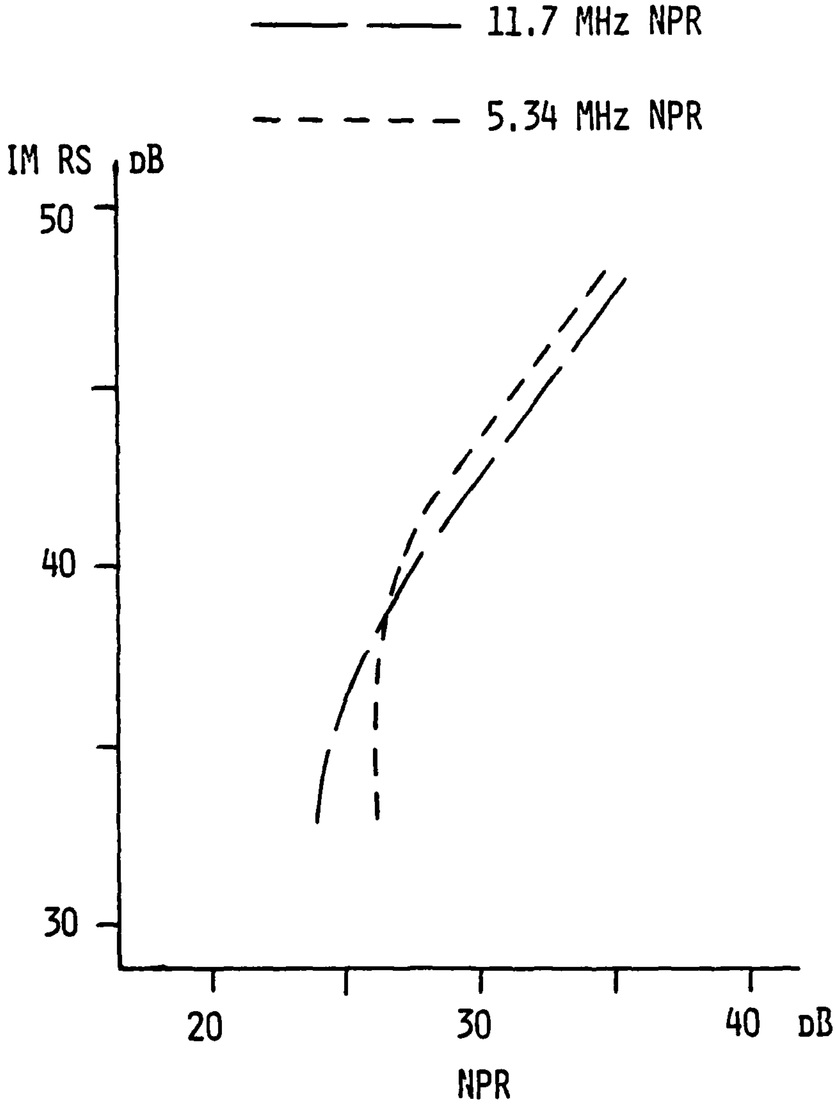



Figure 17. IM Relative Suppression versus NPR

passband of the device, while operating in a linear mode, could be sufficient to obscure a signal of interest.

Using the relative suppression of an order of IM (usually the second or third order) as a specification, presumes that it is the predominent order of distortion. Measuring the NPR to develop an NPR curve gives the order of the distortion without any presumptions. As already shown the slope of the nonlinear region gives that value. To determine the order by the two-tone method, would again require observation and analysis of several orders of IM products at various input levels and frequencies; a lengthy procedure compared to the white noise method. There is also the nontrivial problem of filtering out the harmonics of the test tones at the input.

The use of noise, to load the input, as a more realistic model of the actual HF spectrum has already been discussed. The partial in-phase addition of signal peaks, as is true in the HF spectrum, is more likely to occur with the wideband, multiple frequency noise than with the two-tone input.

4. Combined Effects

In-band intermodulation produces two effects: one is spurious signals which may mask desired signals; the second effect is power consumption and the attendant reduction in dynamic range. Out-of-band IM produces only the second effect. Out-of-band IM can be eliminated by output

filtering. but this just decreases the limited power of the device. Designing an adequate dynamic range will also eliminate this IM, but once the device is driven nonlinear, out-of-band IM may occur. The amount of out-of-band IM can serve as a measure of the design adequacy.

An example of out-of-band IM is shown in figure 18. Wide band noise and a group of signals were applied to the input of the multicoupler, figure 19(a.). The multicoupler was designed for the 2 - 32 MHz HF band, however it did not incorporate any output filtering. As a result, the device showed an output response to 100 MHz with negligible roll off. This provided an examination of out-of-band IM. Figure 18(b.) shows the output spectra. The noise only and signal only outputs above 80 MHz are less than -67 dBm. The output with both signals present at the input shows higher levels due to the out-of-band IM. The signal at 89 MHz is -65 dBm vice -69 dBm and the noise is at -67 dBm vice -75 dBm. A significant portion of the available power is being spent out of band.

By choosing the noise and signal levels properly, the noise was given an envelope or modulation effect that followed the envelope of the signals. This can be seen to some extent in figure 19 by comparing the output to the input at 70 and 88 MHz.

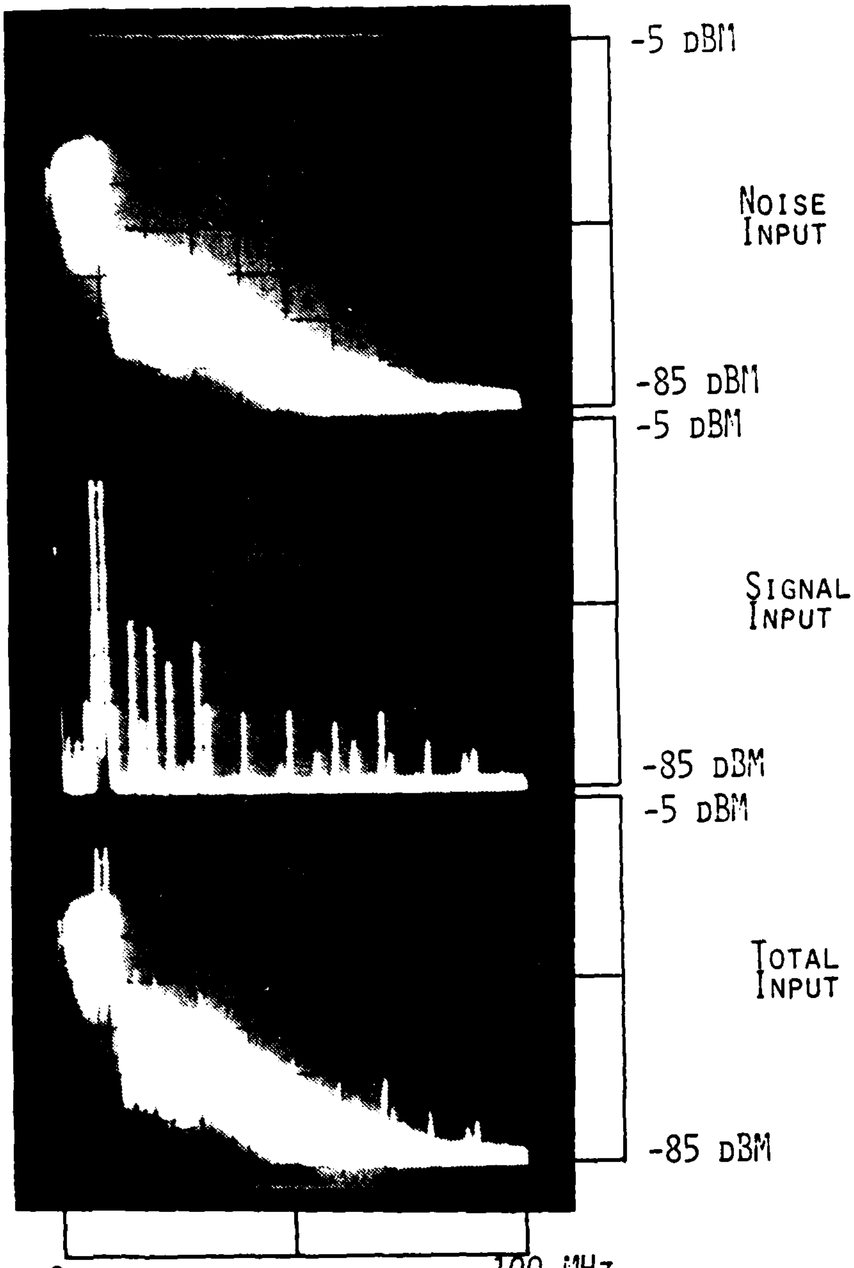



Figure 18 A. Combined Inputs

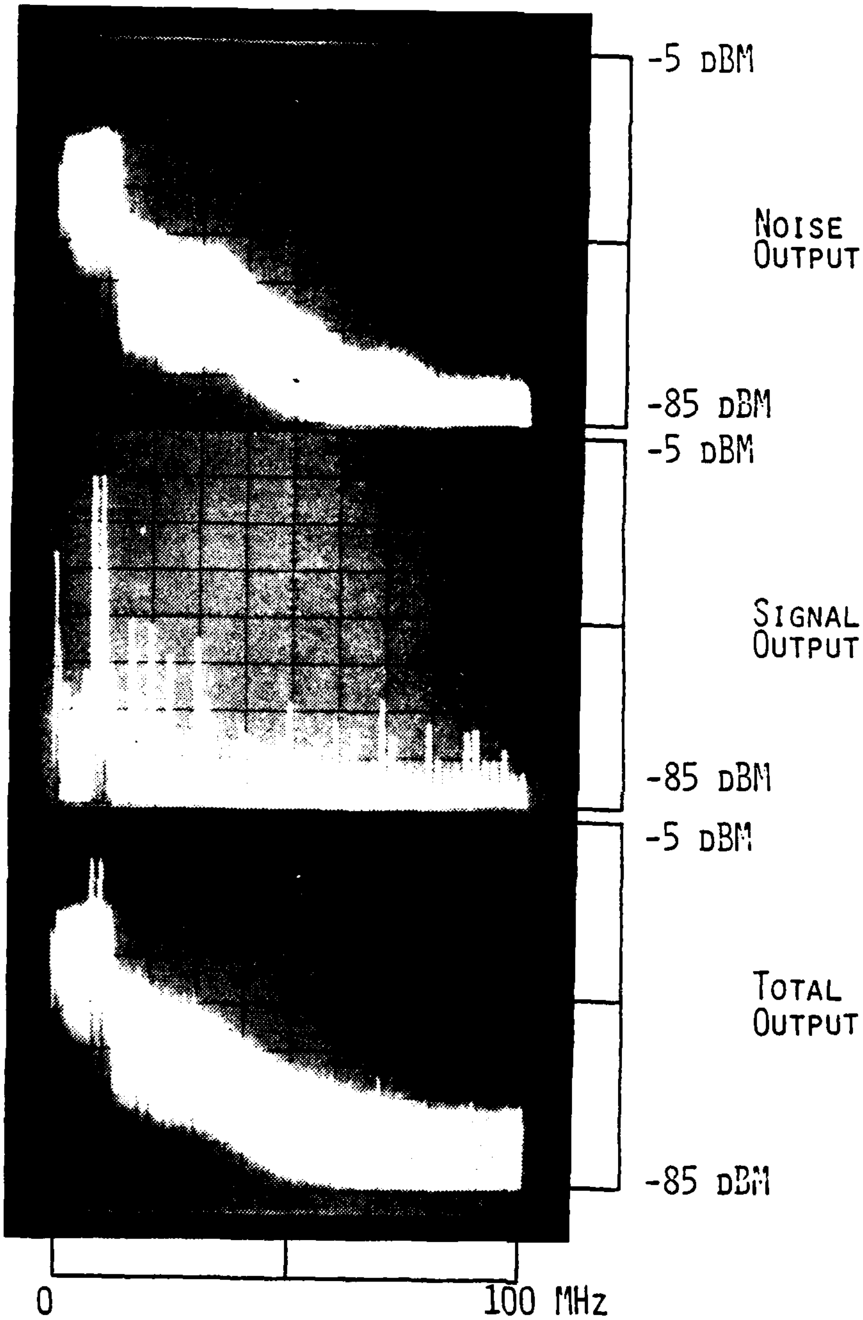



Figure 18 B. Combined Outputs

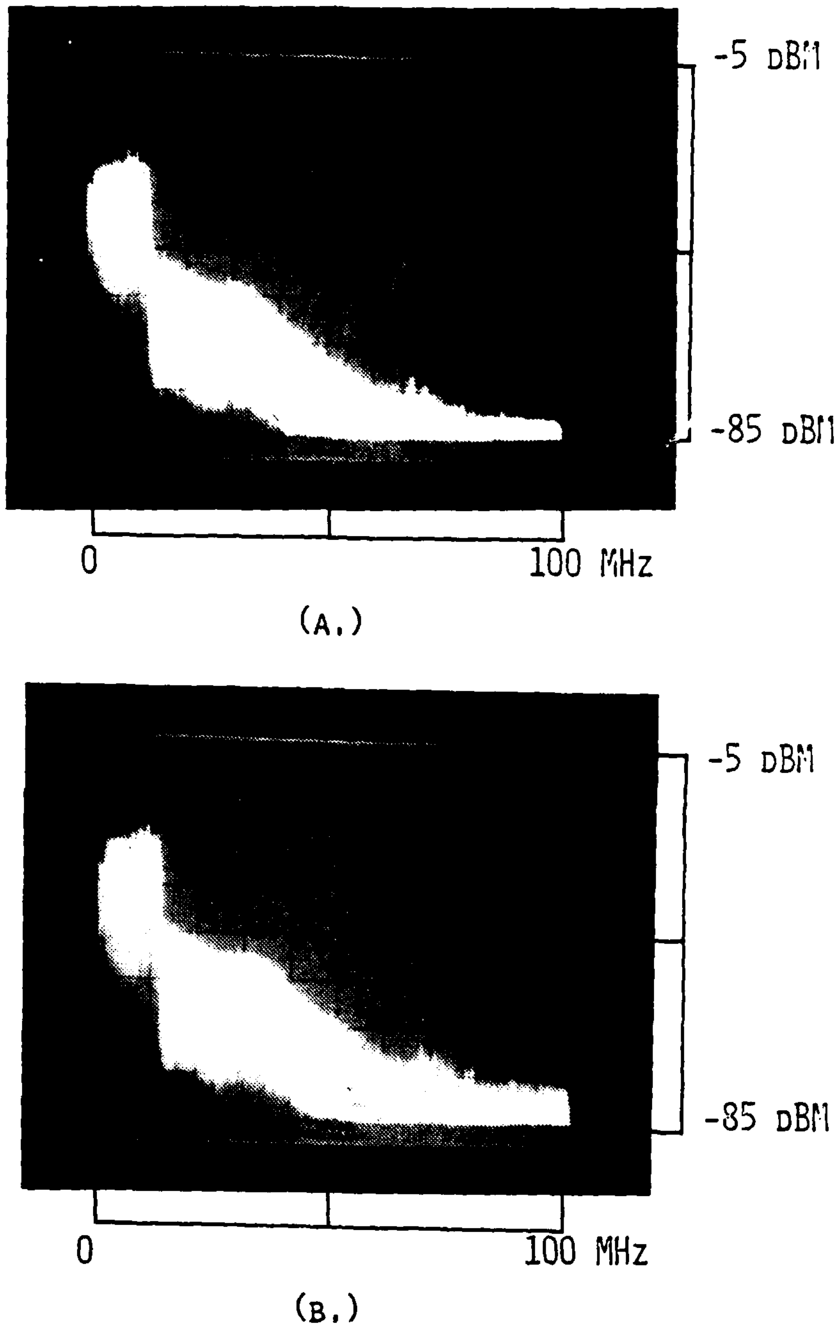



Figure 19. Modulation Effect of Tones on Noise
(A.) Input and (B.) Output

# V. EVALUATION OF WHITE NOISE TEST

## A. ADVANTAGES OF NOISE LOADING

The value of the NPR in the stopband provides an excellent measure of the IM a desired signal would be buried in, when the device is used. The noise generator and receiver need not be colocated, thus actual signal paths or links can be measured. The NPR figure includes intermodulation, cross talk, and thermal noise, all of which contribute to masking a desired signal at the output of the multicoupler. The NPR curve derived from the noise loading test provides information on both linear and nonlinear operation. It also allows for the determination of the predominent order of the IM distortion. The noise test set, consisting of the noise generator, noise receiver, stopband filters, bandlimiting filters, and bandpass filters with the accompanying local oscillators are contained in two units which are compact, weigh approximately 40 pounds each and are relatively easy to handle. The white noise loading technique can be used to measure in-band or out-of-band IM using filter sets for the appropriate frequency. There is no problem of filtering harmonics from the output as with the signal generators. Noise test set costs range from $8,000 for the basic mainframes to $12,000 for the complete set with a nominal set of filters.

## B. DISADVANTAGES OF NOISE LOADING

No specifications or standards for noise loading tests for HF multicouplers are available. These essentially will have to be developed from experience and increased usage of the noise loading technique. The white noise used in the test is uniform in amplitude, the HF spectrum is not. This appears somewhat unrealistic, however it is much closer to the truth than two, singular test tones. This will result in a fairly accurate, perhaps conservative figure of IM product susceptibility. To achieve full loading of the entire multicoupler bandwidth, a noise generator with a white, bandlimited output from 2 to 32 MHz will be needed. Current generators are geared toward telephone system bandwidths which are much less than 33 MHz. The cost of the system will increase if the additional bandwidth is provided.

Figure 14 shows another problem, which is inadequate output (+20 dBm) to drive the high dynamic range multicoupler into nonlinear operation. This may be a trade off with the increasing of the output bandwidth, since more total power will be present in the 33 MHz bandwidth. In either case sufficient output to cause nonlinearity is a must. This problem was also encountered with the 2 - 32 MHz laboratory signal generators used in the two-tone tests. These were also limited to a maximum output of +20 dBm. This might be solved by additional amplification provided by a high dynamic range, low noise preamplifier with a high third

order intercept. The unit under test NPR could be measured by switching in the stopband and bandpass filters, and setting the receiver reference to zero at the output of the preamplifier. The unit under test output is then measured to get the actual NPR reading.

## C. NPR ACCURACY

Reference [3, sections 7.7 and 9.11] contains a detailed description of NPR accuracies. This section will give a summary of that reference. The overall accuracy of the NPR will vary with the bandwidth of the white noise, the center frequency of the stopband and the level of the stopband NPR. If a system has a high NPR (very little IM) that approaches the NPR of the stopband at the generator output, then a correction ranging from 0 to 10 dB is added to the measured system NPR, giving an improvement in the system result. This correction is given in ref. [3, section 7.7, figure 7.7.1] .

In addition there are several corrections that are attributable to the noise generator and noise receiver. These will vary with the equipment that is used. The corrections for the Marconi OA 2090B set are:

Accuracy of generator output:

accuracy of alc monitor $\underline{m}$ = +/- 0.3 dB

accuracy of output attenuator $\underline{g}$ = +/- 0.2 dB

Accuracy of bandlimiting filters (negligible)

Flatness of frequency response $\underline{f}$ = +/- Ø.5 db

Accuracy of bandpass filters (negligible)

Accuracy of receiver attenuators $\underline{r}$ = +/- Ø.4 db

Error due to switching in stopband:

For wideband systems (>7.8 MHz) $\underline{s}$ < Ø.1 dB

The error due to switching in the stopband results from the stopband filter eliminating, from the input, some of the frequency components that contribute to the overall NPR. This could result in a better NPR. For this reason the narrow band "B version" filters are now recommended. Only one stopband filter should be switched in at a time. The equations for combining the above factors are given in ref. [3, section 9.11] and are restated below. For wideband systems, bandwidths of 7.8 MHz or more, the total NPR error is on the order of plus or minus 1.Ø dB.

Linear Region:

$$e = [ m^2 + g^2 + f^2 + r^2 ]^{1/2}$$

Nonlinear Region

$$e = [ (a-1)^2 ( m^2 + g^2 ) + f^2 + r^2 ]^{1/2} + s$$

The slot width error "s" only effects the intermodulation products and is not a factor in the linear region.

The overall accuracy of NPR measurements is wholly acceptable and can be closely controlled. The measurements are straight forward and easily conducted in the laboratory or in the field.

# VI. A NEW SPECIFICATION

Given the significance and viability of using noise loading and NPR measurements to specify intermodulation product susceptibility, some guidelines and requirements for writing an NPR type of IM specification will be presented. Any specific figure of NPR will depend on the specific device and its application. The example offered is for the high dynamic range multicoupler, already discussed.

## A. FACTORS FOR CONSIDERATION

### 1. Noise Test Set Specifications

Current noise test set specifications have been set forth by the International Telecommunications Union committees, CCIR and CCITT, and are quite detailed. Early problems with white noise testing have been resolved. To avoid relocating many of these pitfalls, it would be prudent to utilize test sets that meet recommendation CCIR 399-1. These correspond to the Marconi "B" version equipment. The ITU recommendations for noise levels in telephone channels are of little use, but the sections of the recommendations dealing with the bandlimiting, stopband and bandpass filters are applicable. The equipments now available are geared to the customary telephone test frequencies. In general, there

is an adequate selection of filters available which will reduce the costs and confusion of a proliferation of new filter frequencies.

2. Dynamic Range

The dynamic range of the device impacts directly on the values of maximum NPR and maximum NPR loading. Specifying maximum NPR loading will fix the upper end of the dynamic range. The lower limit would then need to be specified by some minimum signal detectability or other measure. It would probably be best to continue to specify the dynamic range of the device separately, keeping in mind that it is closely tied to the IM product specification.

3. Noise Power Input

Noise power input levels could be specified. If the dynamic range of the device and the range of NPR over the dynamic range is specified, then the noise power input level is implied. If the IM is specified by a single desired NPR figure, then the noise power loading for that level of NPR should be given. This value of noise power input could be a nominal value for the input loading expected (also called the zero transmission level), or it could be the level of input power needed to reach the 1 dB compression point.

The bandlimits also effect the input noise power level. For HF multicouplers the band limits are 2 - 32 MHz and the available noise bandwidth is approximately 12 MHz with a flatness of plus or minus a half of a decibel.

Specifications, written at this time, will have to reflect this bandwidth limitation.

4. NPR Level

The NPR level could be specified in several ways. The NPR could be given as a single value for a given input loading level, such as the maximum NPR loading level or 1 dB compression point level. Specifying an intermediate value should be avoided unless the slope of the linear region of the NPR curve is known or also specified, and that median value is in the linear region. In this case the dynamic range specification would have to be given also.

If the NPR was specified for a maximum NPR loading level, a given slope of the linear range and a minimum detectability, then the dynamic range would not need to be separately specified. The NPR could be stated as a minimum to maximum range, with a separate dynamic range specification. The coincidence of the 1 dB compression point loading level and the maximum NPR loading level should not be assumed. At 1 dB compression, the device may be operating in either the maximum NPR or nonlinear region. Although additional study is needed on this point, section IV.C.2 indicated that maximum NPR may occur before the 1 dB compression level.

Determining a reasonable value of NPR will be difficult initially. A selection can be made by comparing the NPR of a device with its known third order IM

specification. Empirical relationships such as figure 17 may be usable until exact relationships and experience with usage have been developed.

5. Stopbands

The stopband filter specifications should be taken from the current ITU recommendations. A specification should state the number and center frequencies of the stopbands at which NPR will be measured. The variation of NPR with frequency calls for a sampling of a minimum of three stopbands. CCIR/CCITT recommendations show sampling at intervals of 500 KHz to 7 Mhz, depending on the device bandwidth. Spacing between stopbands should not exceed seven to ten megahertz. The use of those stopband frequencies available on the market would produce satisfactory results even with the lack of filters for frequencies above 15 MHz.

Out-of-band stopbands can be used to take out of band measurements provided the filter sets are available for the frequencies desired. Out-of-band IM which might degrade total system performance could be observed on a spectrum analyzer if the stopband and bandpass filter sets are not available.

6. Order of Distortion

A new area of specification may be developed around the NPR curve. Since the order of predominant distortion can be determined from the NPR curve nonlinear region, it might be desirable to specify this order of distortion. This

specification would reflect the desired gracefulness of the system degradation. This figure would have a major effect on the device design and if poorly chosen could lead to inherent expense or capability not required. In the area of class C amplifiers or hardlimiting transponders, this type of specification could have important impact on specifying or quantizing the system intermodulation.

B. EXAMPLE SPECIFICATIONS

From the discussion and data presented, a hypothetical specification for the experimental high dynamic range multicoupler could be written. The 1 dB compression point is known to be +24 dBm. The signals likely to be encountered range from +5.5 dBm to -60 dBm. To account for the in-phase additions, a log-normal signal voltage distribution, Appendix A, requires an additional 21 dB of dynamic range for a total of 86.5 dB. Assume that with nominal loading of +5.5 dBm, a signal of -60 dBm must be recoverable. This would reqire an NPR of 65.5 dB. Comparing this to figure 17, an equivalent third order IM RS would be -90 dB. This may seem to be an excessive figure when compared with current multicoupler specifications. However, severe IM problems exist in these multicouplers. It is worthwhile to realize that the back to back (noise generator connected directly to the receiver) NPR of the test set is around 70 to 75 dB. Measurements at a 65.5 dB level of NPR require close

attention to the errors already discussed. A summary of the above data is:

| | |
|---|---|
| 1 dB compression point | +24 dBm |
| Dynamic range | 66.5 dB |
| NPR at 5.5 dBm loading | 65.5 dB |

The sample specification might read:

The measured stopband NPR for intermodulation, thermal noise and cross talk shall be not less than 65.5 dB for an input loading of white noise of a bandwidth from 316 KHz to 12360 KHz with a power level of +5.5 dBm. The NPR shall be sampled at stopbands with center frequencies of 5.34 MHz and 11.7 MHz. The noise test set used shall comply with recommendations CCIR 399-1.

OR

The measured stopband NPR at 5.34 MHz and 11.7 MHz shall be greater than 75 dB for bandlimited, white noise loading less than -40 dBm and a maximum NPR of 65.5 dB for noise loading of +24 dBm. The NPR shall have a linear characteristic between these points. The white noise will be bandlimited at 316 KHz and 12360 KHz. The noise test set shall meet current CCIR/CCITT recommendations.

C. TEST PROCEDURE

The test procedure is straight forward. The back to back NPR of the test set should be checked using the required input power at each stopband to be measured. These are recorded and would be used to apply the high NPR correction, if needed. The unit under test is then connected between the generator and receiver, figure 12. The bandlimiting filters and noise loading level are set. For each stopband/bandpass filter pair, the receiver reference level is set with the bandpass filter switched in. Then the stopband filter is switched in and the receiver attenuators are adjusted to restore the reference level. The NPR is read from the attenuator dial scales and the necessary corrections are applied. This procedure is based upon a knowledge of the Marconi Instruments OA 2090B Noise Test Set and should be verified against manufacturers instructions if other test sets are used.

## VII. CONCLUSIONS

The noise loading technique has been widely accepted by the ITU, Bell System, Intelsat, DOD and other agencies involved with international and domestic telephone systems. This method has been used to successfully test multiple channel, wideband translation equipment, repeaters, transponders and cables. The noise loading technique has been developed, tested and standardized in these respects. Application of this technique to wideband HF devices is a new development. No established standards are available for HF amplifiers or multicouplers, but the application of the technique is wholly valid and reasonable. Specifications, practices and expertise will develop as usage and acceptance increase.

The measured NPR gives an accurate value of the intermodulation products that are generated by the nonlinearities or power limitations of the multicoupler. Methods for identifying both thermal noise and that portion of the intermodulation below the thermal noise level are available.ref. [3],[4] and [5]. Error correction tecaniques can reduce NPR errors to less than one decibel.

Additional research should be directed toward the determination of the relationship between the maximum NPR loading and 1 dB compression points to determine if the

specification of the upper limit of the dynamic range by using the maximum NPR loading point, is preferable.

Determination of the relationship of the third order intercept to the NPR will allow conversion of old IM product susceptibility specifications to the NPR type of specification. This would allow a rapid broadening of a base for NPR specification, if the relationship can be quantified.

Intermodulation product production is dependent on the nonlinear action of the device. Additional knowledge about the nature of instantaneous signal voltage distribution and the frequency with which in-phase additions occur, will broaden the understanding of how these devices are driven to the nonlinear region. Combining this with a knowledge of the device relaxation time and maximum NPR loading will provide a basis for exact specifications of IM product susceptibility that will minimize costs and provide maximum performance.

Additional research should also be conducted to determine if IM product tests are sufficient with the current bandwidth limits (12 MHz) of the white noise or whether the full 2 - 32 MHz bandwidth will be necessary. Sufficient justification, in performance gained, will be necessary to validate the cost increases for the 30 MHz bandwidth test sets.

# APPENDIX A

The distribution of signal peak voltages impacts directly upon the dynamic range of an RF device. Two hypotheses in this field are currently being debated. The debate centers on the nature of the distribution of peak signal voltage versus the frequency of occurrence of that voltage. The distribution determines the additional amount of dynamic range, over the observed signal values, that is needed to withstand the in-phase addition of small signals that results in a sudden overload of the device input. The two distributions being suggested as models are:

1. That signal voltages are log-normal distributed, and an additional 21 dB of dynamic range is needed.

2. That signal voltages are gaussian distributed, and an additional 13 dB of dynamic range is needed.

The points to be considered in arguing these two views from an HF communications viewpoint are many and varied. They involve consideration of the near field, far field, Rayleigh fading, D layer absorption, geographic location, polarization, atmospheric and man-made noise and other factors.

A cursory look at the problem was undertaken as part of the preparation of this paper. Figure 22 shows the test equipment configuration. The procedure was to use the spectrum analyzer to examine the HF spectrum for 2 to 32 MHz in 500 KHz segments. Each segment was photographed for record. The entire scan from 2 to 32 MHz was done once during daylight and once during the night, to record two distinct propagation conditions. The entire scan took approximately four hours to record. Therefore, the frequency scan also represents a time scan. The signals recorded on film were broken into 5 dB ranges. The total number of signal peaks in each 5 dB range were counted.

Several inaccuracies were induced using this form of measurement. No error correction was attempted due to the overall accuracy desired. These errors include: the "Q" of the wire antenna was insufficient for the bandwidth measured; the antenna was horizontally polarized; and high signal peaks masked low level signals on nearby frequencies due to the nature of the photograph and the CRT trace. No signals above -30 dBm were observed. The spectrum analyzer noise floor was -120 dBm. Signals below -115 dBm were omitted to prevent inclusion of spectrum analyzer noise.

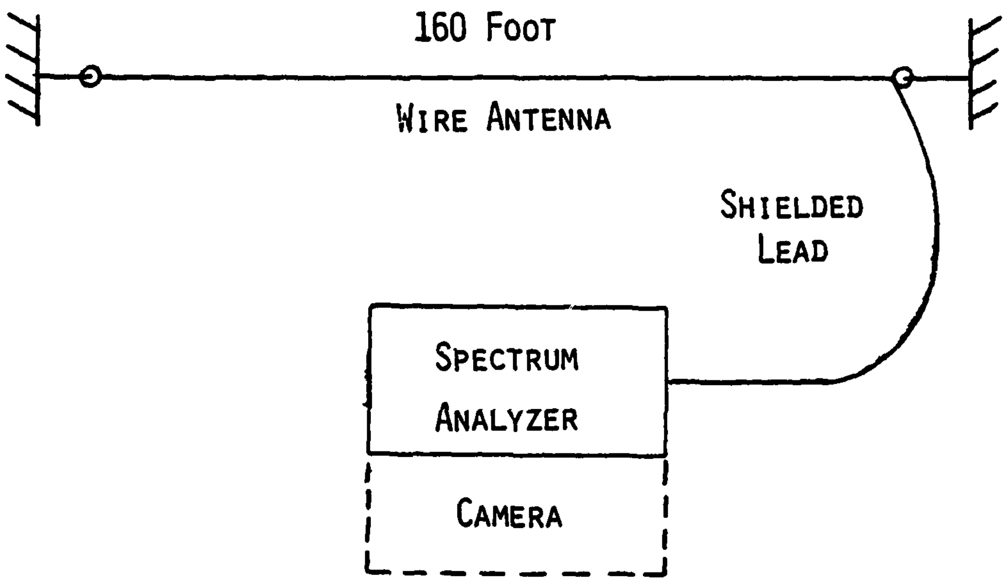



Figure 20. HF Spectrum Measurement Equipment Configuration

The spectrum analyzer settings were:

| | |
|---|---|
| IF Bandwidth | 3.3 KHz |
| Verticle scale | 10 dB / division |
| Log dB reference | -30 to -60 dBm as needed |
| Horizontal scale | 50 KHz / division |
| Horizontal sweep | 5 sec / division |
| Total horizontal axis | 500 KHz |

Figure 21 contains a sample of the photographs taken during the daytime survey. A total of 12095 signals were observed during the day and night surveys. The statistical data are:

| | | |
|---|---|---|
| Day | | |
| | mean | -100 dBm |
| | stnd. dev. | 14 dB |
| | signals counted | 8214 |
| Night | | |
| | mean | -95 dBm |
| | stnd. dev. | 15 dB |
| | signals counted | 3881 |
| Total | | |
| | mean | -98 dBm |
| | stnd. dev. | 15 dB |
| | signals counted | 12095 |

Figure 22 shows the total distribution of the signals plotted in dBm on linear scales. If the signal voltage value

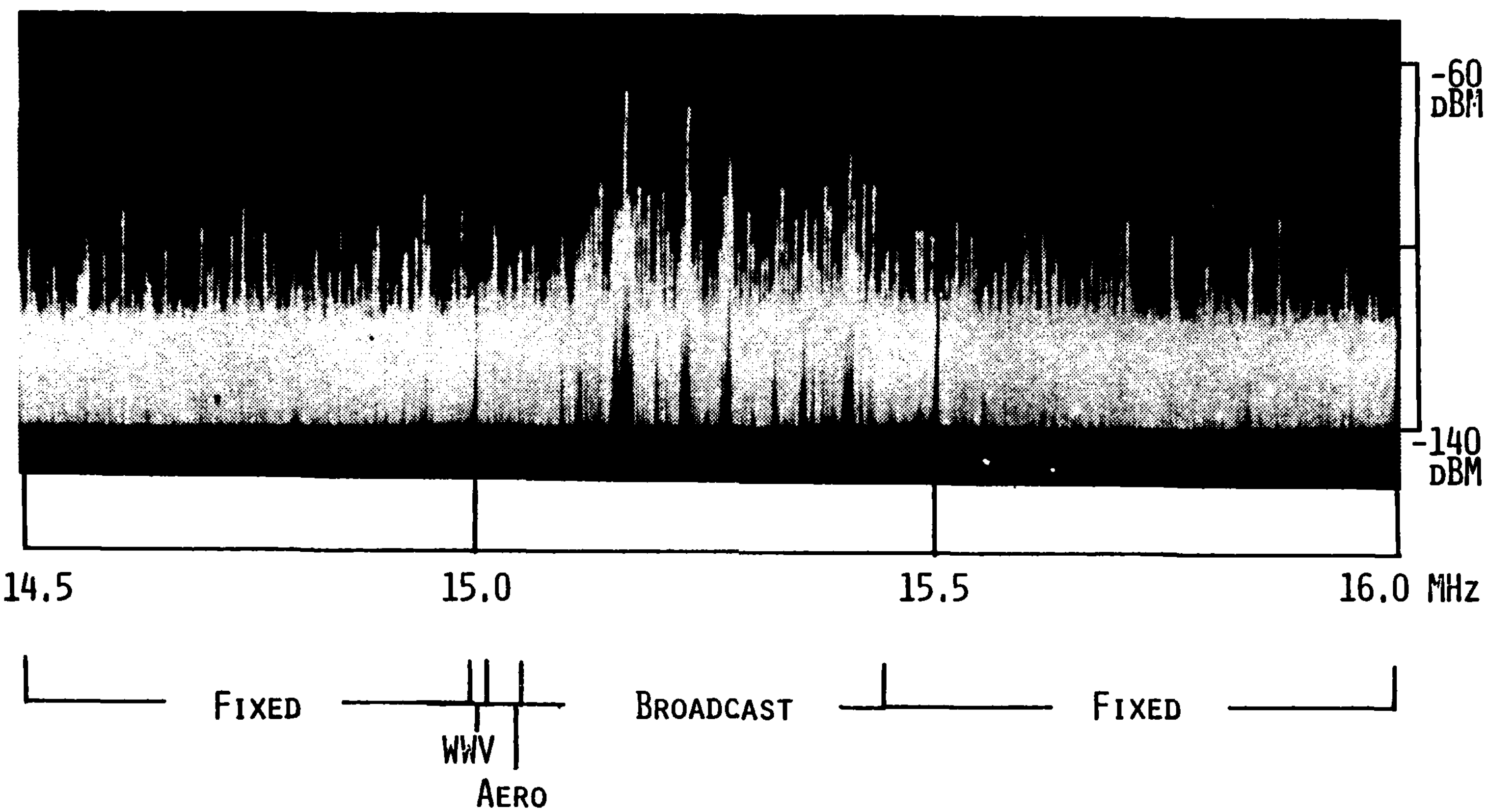



FIGURE 21. HF SPECTRUM SAMPLE

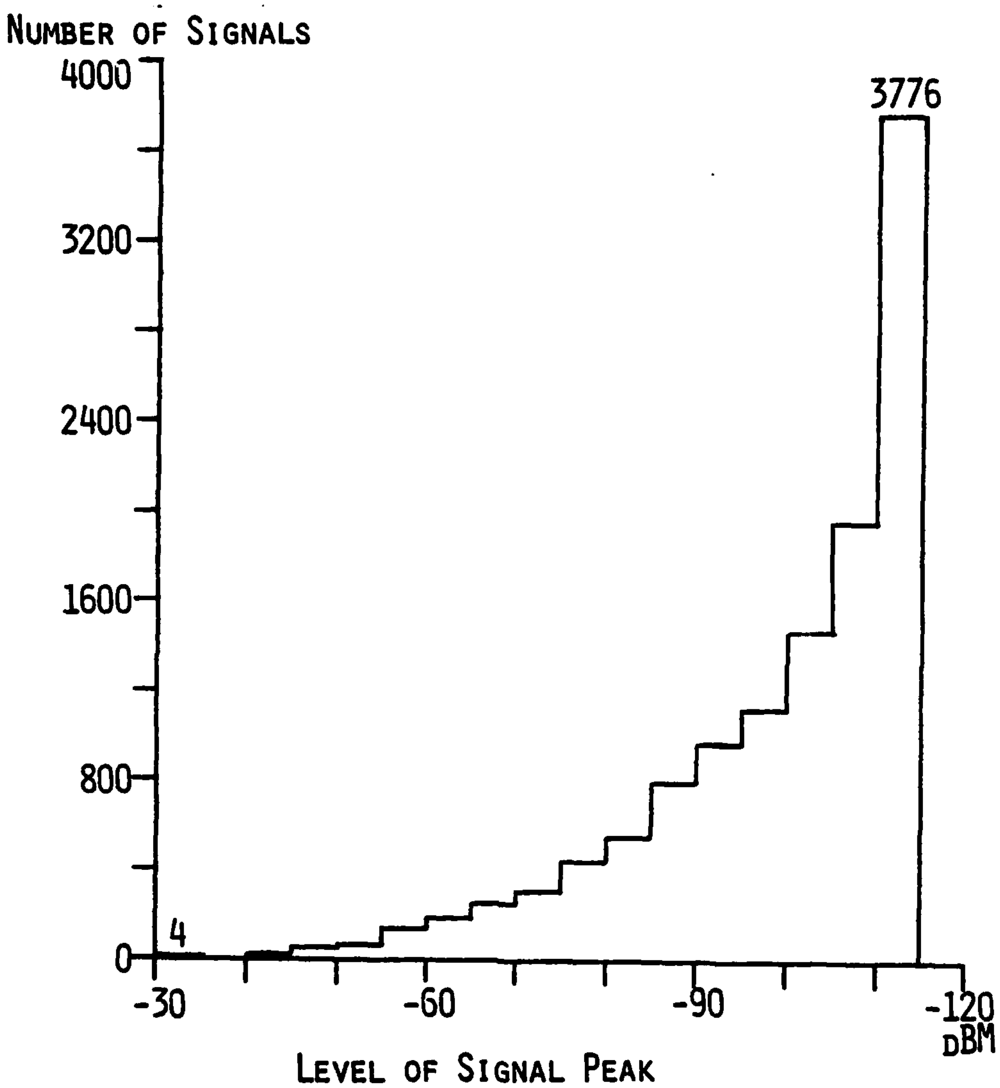



Figure 22. Spectrum Survey Results 2 - 32 MHz

is scaled and then plotted on log-normal or gaussian probability paper, the data will give a straight line on the paper of the proper distribution. Reference [6] was used for this procedure of scaling and ordering the data. The data was plotted in straight line segments representing the 5 dB range and the range of the number of signals in it. Figures 23 and 24 show the log-normal and gaussian plots respectively. The conclusion that can be drawn from such plots is whether the represented distribution is adequate, questionable or inadequate as a model of the actual signal distribution. When truncated data or samples are taken, the curve will usually show deviation from a straight line near the ends [6].

Figure 23 shows that for the signals measured the log-normal distribution is an adequate statistical descriptor. Figure 24 shows that the normal or gaussian distribution is an inadequate descriptor. It would be concluded from this, that the dynamic range of a device receiving the 2 - 32 MHz spectrum should include an additional 21 dB as opposed to 13 dB.

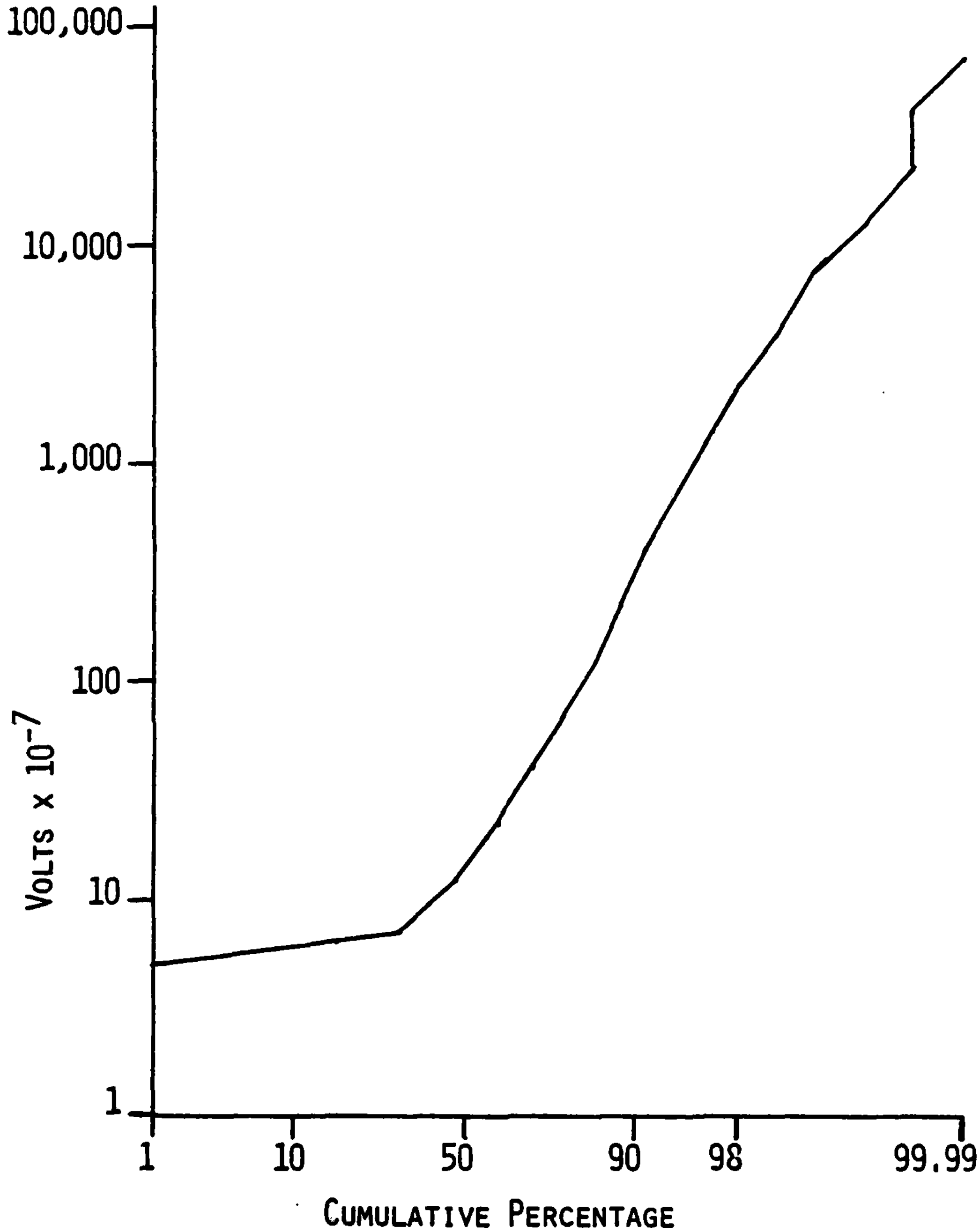



Figure 23. Log-normal Probability Plot of Signal Voltage

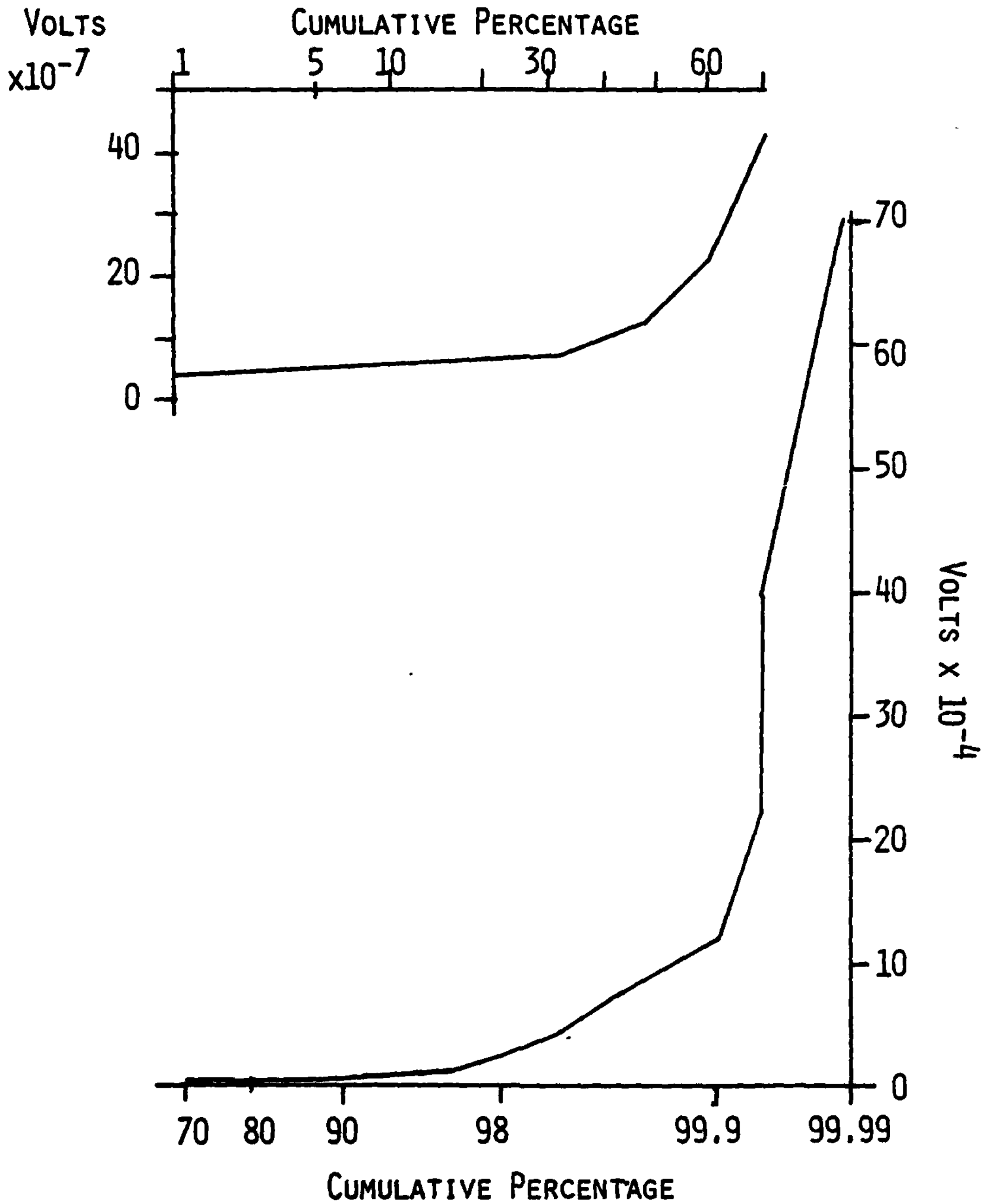



Figure 24. Gaussian Probability Plot of Signal Voltage

## APPENDIX B

The step by step procedure for taking an NPR measurement is presented below. The procedure is for the Marconi Instruments OA 2092B White Noise Test Set. Reference [5] should be consulted when using this equipment. The procedure may vary for other noise test sets.

A back to back NPR should be taken for each generator output level and stopband to be used. This value may be needed to apply the error corrections. The back to back test is made by connecting the generator output directly to the receiver input. The procedure below applies to both the back to back test and the system test.

The connections for the system test and back to back test must be made with cables that match the generator output and receiver input impedances (75 ohms). For system tests the generator and receiver can be at separate locations, such as at opposite ends of a multiplexed cable or microwave link. A minimum of three, widely spaced stopbands should be sampled.

The procedure is:

1. Turn on the generator and receiver.

2. Switch in the desired highpass and lowpass bandlimiting filters on the generator.

3. Switch on the noise output and adjust it to the level that will be used for the system test.

4. Switch in the desired receiver bandpass filter.

5. Using the "Reference Set" knob, set the receiver meter to the zero reference level. Adjust the attenuators if necessary. The attenuator scales can be set to zero, independently, without changing the attenuator knob position.

6. Switch in the generator stopband filter corresponding to the selected receiver bandpass filter.

7. Adjust the attenuator knobs to restore the zero reference. Do not change the "Reference Set" position. The NPR can be read from the attenuator knobs and the receiver meter to an accuracy of 0.2 dB.

8. Apply any error corrections that are needed.

9. Repeat the above procedure for the remaining stopband/bandpass frequencies to be tested.

DO NOT SWITCH MORE THAN ONE STOPBAND FILTER IN LINE AT A TIME. Otherwise a large error will result (CCITT 228).

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